Convocatorias 2017
Proyectos EXCELENCIA y Proyectos RETOS
AGENCIA ESTATAL DE INVESTIGACIÓN

AVISO IMPORTANTE

En virtud del artículo 16 de la convocatoria **NO SE ACEPTARÁN NI SERÁN SUBSANABLES MEMORIAS CIENTÍFICO-TÉCNICAS** que no se presenten en este formato.

Es obligatorio que la memoria contenga los tres apartados (A, B y C). La parte C de la memoria no podrá exceder de 20 páginas.

Lea detenidamente las instrucciones para rellenar correctamente esta memoria, disponibles en la web de la convocatoria.

Parte A: RESUMEN DE LA PROPUESTA/SUMMARY OF THE PROPOSAL

INVESTIGADOR PRINCIPAL 1 (Nombre y apellidos)**:**
Raffaele Bernardello
INVESTIGADOR PRINCIPAL 2 (Nombre y apellidos)**:**

TÍTULO DEL PROYECTO: Predicciones decenales de la absorción de carbono en el Océano del Sur e impacto de la incertidumbre en la bomba biológica de carbono.

ACRÓNIMO: DeCUSO

RESUMEN Máximo 3500 caracteres (incluyendo espacios en blanco):

El reciente acuerdo de París sobre clima vincula los países participantes (entre ellos España y la totalidad de la UE) a adoptar medidas para reducir las emisiones de carbono antropogenico con el objetivo de mantener el calentamiento global por debajo de 2ºC hasta el final de este siglo. Esto se traduce en la necesidad de estimar con precisión las emisiones de CO2 compatibles con mucha antelación para asegurarse de cumplir con los objetivos. Sin embargo, cierta precisión en la estimación de las emisiones de CO2 compatibles se puede alcanzar solo si todas las fuentes y todos los sumideros de carbono atmosférico se conocen con la máxima exactitud.

El océano representa un sumidero importante al absorber hasta un 25% del carbono antropogenico emitido por las actividades humanas proporcionando un servicio esencial para la sociedad. En particular, se estima que el Océano del Sur absorba hasta el 50% del carbono antropogenico que entra en el océano. Sin embargo, debido a su ubicación remota, esta área ha sido poco observada y destaca como un desierto de datos, especialmente en invierno. Aunque se asuma que sean procesos físicos los responsables de la mayoría de la absorción de carbono antropogenico, un conjunto de mecanismos biogeoquímicos (la llamada Bomba Biológica de Carbono, BCP) son clave para mantener la mayoría del gradiente vertical de carbono inorgánico disuelto, lo cual determina en ultima instancia el flujo de CO2 entre atmósfera y océano. La BCP en el Océano del Sur es especialmente poco conocida y la incertidumbre en la estimación de su eficiencia es lo bastante grande como para confundir estimaciones de absorción de carbono total. Ademas de las dinámicas complejas propias del ciclo del carbono y de sus interacciones con un entorno tan dinámico, el Océano del Sur se caracteriza por unas marcadas oscilaciones decenales relacionadas con la variabilidad climática a escala global. Esta característica, en el pasado ha obstaculizado intentos de detectar un trend significativo en la absorción de carbono pero, al mismo tiempo podría representar una fuente de predictibilidad a escala decenal.

Motivadas por estos retos, las actividades propuestas en DeCUSO tienen como objetivo proporcionar un examen exhaustivo de nuestra habilidad de predecir la absorción de carbono en escalas de tiempo que van de un mes hasta un decenio de antelación. Ademas, esta propuesta tiene como objetivo el mejoramiento de nuestra comprensión de como la incertidumbre en la absorción de carbono mediado por la BCP se propaga a la estimación de la absorción de carbono total. Para lograr estos objetivos se plantean tres work packages. Primero, se implementará el llamado Transport Matrix Method (TMM) para ser usado con el Eart System Model (ESM) EC-Earth. Este método permite equilibrar la componente biogeoquímica de EC-Earth en una fracción del tiempo que se necesitaría si se usara el ESM mismo. El equilibrar la componente biogeoquímica de un ESM es un requerimiento esencial antes de poder llevar a cabo cualquier evaluación de sensibilidad del modelo. Este primer work package proporcionará las herramientas necesarias para generar las condiciones iniciales que se usarán para las predicciones decenales de absorción de carbono del segundo work package. Finalmente, en el tercer work package, las actividades de modelización con el método TMM estarán dirigidas al estudio del impacto de la incertidumbre en la representación de la BCP sobre la absorción de carbono total.

PALABRAS CLAVE: Absorción de carbono, Océano del Sur, Bomba biológica de carbono, Predicciones decenales, Método de matrices de transporte, EC-Earth, Earth System Model

TITLE OF THE PROJECT: Decadal predictions of Carbon Uptake in the Southern Ocean and impact of the biological carbon pump uncertainty.

ACRONYM: DeCUSO

SUMMARY Maximum 3500 characters (including spaces):

The recent COP21 Paris agreement on climate ties the participating countries (Spain and the whole EU among them) to take actions to reduce anthropogenic carbon emissions in order to contain global warming within 2ºC by the end of this century. This translates into the necessity to precisely estimate the compatible CO2 emissions well ahead of time to make sure targets are met. However, precision in the estimate of compatible CO2 emissions can be achieved only if all sources and sinks of atmospheric carbon are known with the highest possible accuracy.

The ocean represents one major sink as it takes up about 25% of the anthropogenic carbon emitted by human activities providing an essential service to society. Particularly, the Southern Ocean is estimated to absorb up to 50% of the anthropogenic carbon entering the ocean. However, because of its remoteness, this area is sparsely observed and it stands out as a data desert, particularly in the winter time. Although physical mechanisms are commonly assumed to be the drivers of most anthropogenic carbon uptake, a set of mechanisms involving ocean biogeochemical processes (the so-called Biological Carbon Pump, BCP) are key to maintain most of the vertical gradient of dissolved inorganic carbon which ultimately drives the flux of CO2 between atmosphere and ocean. The BCP is particularly poorly constrained in the Southern Ocean and the uncertainty in the estimate of its strength is large enough to confound accurate estimates of carbon uptake. Moreover, in addition to complex dynamics specific to the ocean carbon cycle and its interactions with a highly dynamical environment, the Southern Ocean is characterized by marked decadal oscillations linked to global-scale climate modes of variability. This characteristic has hampered past attempts to detect trends in carbon uptake but, at the same time, could represent a source of predictability on decadal timescale.

Motivated by these challenges, the activities proposed within DeCUSO have as objective to provide an extensive assessment of our ability to predict the ocean carbon uptake on timescales ranging from one month to one decade ahead. Moreover, this proposal aims at improving our understanding of how uncertainty in the carbon uptake mediated by the BCP is propagated to the total carbon uptake estimate. To achieve these ambitious objectives three work packages are planned. First, members of DeCUSO will implement the Transport Matrix Method (TMM) to be used with the Earth System Model (ESM) EC-Earth. This will allow to equilibrate the biogeochemical component of EC-Earth in a fraction of the time it would take if the actual ESM was used. The equilibration of the biogeochemical component of an ESM is an essential prerequisite before performing any model evaluation, test or sensitivity study. This first work package will provide the tools to produce initial conditions for the decadal predictions of carbon uptake to be performed in the second work package. Finally, in the third work package, modeling activities using the TMM will be directed at evaluating the impact of the uncertainty in the representation of the BCP on total carbon uptake.

KEY WORDS: Carbon uptake, Southern Ocean, Biological carbon pump, Decadal predictions, Transport Matrix Method, EC-Earth, Earth System Model.

Parte B: INFORMACIÓN ESPECÍFICA DEL EQUIPO

B.1. FINANCIACIÓN PÚBLICA Y PRIVADA (PROYECTOS Y/O CONTRATOS DE I+D+I) DEL EQUIPO DE INVESTIGACIÓN (repita la secuencia tantas veces como se precise hasta un máximo de 10 proyectos y/o contratos).

1. Investigador del equipo de investigación que participa en el proyecto/contrato (nombre y apellidos): Pierre Antoine Bretonniere
   Referencia del proyecto: SPECS, GA 308378
   Título: Seasonal-to-decadal climate Prediction for the improvement of European Climate Services
   Investigador principal (nombre y apellidos): Francisco Doblas Reyes (Also coordinator)
   Entidad financiadora: European Commission-FP7
   Duración (fecha inicio - fecha fin, en formato DD/MM/AAAA): 01/11/2012-31/01/2017
   Financiación recibida (en euros): 1.615.305,75€ (total funding budget 8.224.862€)
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

2. Investigador del equipo de investigación que participa en el proyecto/contrato (nombre y apellidos): Pierre Antoine Bretonniere
   Referencia del proyecto: PREFACE, GA 603521
   Título: Enhancing prediction of tropical Atlantic climate and its impacts
   Investigador principal (nombre y apellidos): Francisco Doblas Reyes (Coordinator Noel Keenlyside, Univ. Bergen)
   Entidad financiadora: European Commission- FP7
   Duración (fecha inicio - fecha fin, en formato DD/MM/AAAA): 01/11/2015-31/10/2017
   Financiación recibida (en euros): 266.569€ (total funding budget 8.999.433€)
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

3. Investigador del equipo de investigación que participa en el proyecto/contrato (nombre y apellidos): Pierre Antoine Bretonniere, Nicolau Manubens
   Referencia del proyecto: ITT Ref: C3S_51
   Título: QA4Seas-Quality Assessment Strategies for Multi-Model Seasonal Forecasts
   Investigador principal (nombre y apellidos): Francisco Doblas Reyes
   Entidad financiadora: ECMWF (Copernicus Climate Change Service)
   Duración (fecha inicio - fecha fin, en formato DD/MM/AAAA): 01/07/2016-30/09/2018
   Financiación recibida (en euros): 731.214,40€ (total funding budget 1.681.760€)
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

4. Investigador del equipo de investigación que participa en el proyecto/contrato (nombre y apellidos): Pierre Antoine Bretonniere, Niculau Manubens
   Referencia del proyecto: ITT Ref:C3S_34a – Lot 2
   Título: MAGIC- Metrics and Access to Global Indices for Climate Projections
   Investigador principal (nombre y apellidos): Francisco Doblas Reyes
   Entidad financiadora: ECMWF (Copernicus Climate Change Service)
   Duración (fecha inicio - fecha fin, en formato DD/MM/AAAA): 01/10/2016-31/03/2019
   Financiación recibida (en euros): 170.000€ (total funding budget 1.140.000€)
   Relación con el proyecto que se presenta: está algo relacionado
   Estado del proyecto o contrato: concedido

5. Investigador del equipo de investigación que participa en el proyecto/contrato (nombre y apellidos): n/a
   Referencia del proyecto: CCI-PRGRM-EOPS-SW-13-0043
   Título: Climate Modelling User Group "optional extra" for seasonal predictions
   Investigador principal (nombre y apellidos): Virginie Guemas (coordinator Paul van der Linden, MetOffice)

Entidad financiadora: European Space Agency (ESA)
Duración (fecha inicio - fecha fin, en formato DD/MM/AAAA): 01/10/2015-30/06/2017
Financiación recibida (en euros): 92.100,00 € (total funding budget 152.100€)
Relación con el proyecto que se presenta: está algo relacionado
Estado del proyecto o contrato: concedido

B.2. RELACIÓN DE LAS PERSONAS NO DOCTORES QUE COMPONEN EL EQUIPO DE TRABAJO (se recuerda que los datos de los doctores del equipo de trabajo y de los componentes del equipo de investigación no se solicitan aquí). Repita la siguiente secuencia tantas veces como precise.

1. Nombre y apellidos:
Titulación: licenciado/ingeniero/graduado/máster/formación profesional/otros (especificar)
Tipo de contrato: en formación/contratado/técnico/entidad extranjera/otros (especificar)

Parte C: DOCUMENTO CIENTÍFICO. Máximo 20 páginas.

C.1. PROPUESTA CIENTÍFICA

1. Introduction and state-of-the-art

1.1 Context and motivation

The recent COP21 Paris agreement on climate ties the participating countries (Spain and the whole EU among them) to take actions to reduce anthropogenic carbon emissions in order to contain global warming within 2ºC by the end of this century. This translates into the necessity to precisely estimate the compatible CO_2 emissions well ahead of time to make sure targets are met. However, precision in the estimate of compatible CO_2 emissions can be achieved only if all sources and sinks of atmospheric carbon are known with the highest possible accuracy.

The ocean represents one major sink as it takes up about 25% of the anthropogenic carbon emitted by human activities providing an essential service to society (Le Quere et al., 2016). However, changes in circulation and in the physical state of the ocean driven by both natural variability and ongoing climate change could alter the capacity of the ocean to absorb carbon. This could cause more CO_2 to be left in the atmosphere resulting in an acceleration of climate change, referred to as the carbon feedback.

Our best tools to predict the future evolution of the carbon feedback are Earth System Models (ESMs). These are complex numerical representations of the primitive equations of fluid motion for both the atmosphere and ocean. Coupled to these are representations of other climate-relevant processes (i.e. land hydrological cycles, sea-ice and cloud formation etc.) and of biogeochemical cycles of elements influencing the climate like carbon. ESMs are used to predict future climate under prescribed atmospheric CO_2 trajectories corresponding to different socio-economic scenarios. Once all the carbon sinks (among them the ocean) are taken into account by the model, the amount of CO_2 that can be emitted in order to stay within the limits of a given scenario is calculated. This amount is the compatible CO_2 emission.

Overall, the uncertainty given by state-of-the-art ESMs on ocean carbon uptake over the period 1986-2005 was 0.2 Pg C year^{-1} (Anav et al., 2013). Although such uncertainty translates to only a few parts per million of atmospheric CO_2, it is more than enough to thwart the ability of policy makers to take informed decisions on the measures needed to meet target emissions. For example, 0.2 Pg C is equivalent to the amount of carbon emitted in one year by 590 medium-size thermoelectric power plants working on natural gas[1]. As an example, when scaled down by Spain's contribution to global CO_2 emissions (0.73% in 2013) the uncertainty is equivalent to 4 such medium-size power plants. To replace one plant with newly installed wind turbines requires an investment of approximately 665 million €[2] while the equivalent cost of newly installed solar power would be around 1.1 billion € per plant[3]. So, for Spain it would mean an uncertainty on when and whether an investment of between 2.7 (all wind) and 4.3 (all solar) billion € has to be made.

Furthermore, an uncertainty of 0.2 Pg C yr^{-1} is an optimistic estimate computed as the standard deviation of the suite of ESMs that provided results for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5). Frolicher et al. (2015) pointed out that this estimate of the uncertainty could be biased low due to similarities between models. In fact different models often share the same formulations for one or more components and thus they are not strictly independent from each other (Knutti et al., 2013).

The ability to have a more precise figure on compatible emissions will be a capital asset for policy makers to effectively plan our society's transition to a sustainable post-oil economy. Such transition is already under-way thanks also to the unprecedented coverage of the participation at COP21. Countries who have submitted pledges cover 90% of global energy production. However, pledges are non-binding and subject to internal political shifts. At this crucial time in humanity's history, it is then

1. Based on an installed power of 400 Mw, an assumed yearly operating time of 6000 hours and an average of 518 g CO2 /Kwh - from Energy and Climate Change, World Energy Outlook 2015, Special Briefing for COP21 -International Energy Agency.

2. Based on a cost of 3.33 million € per 2Mw installed, from http://www.windustry.org

3. Based on a cost of €2.71/Kw from http://marketrealist.com

paramount that every possible effort is made to keep public mainstream and, consequently, policy makers' attention on the targets provided by the climate science community. These targets need to be as precise as possible to be trustworthy and every effort in this direction should be sustained over the next years. At this time, the scientific community can not afford a failure as the level of attention of the world on their advice is unprecedented. Not being able to provide robust answers could undermine the current momentum with unforeseen dramatic consequences.

1.2 Outline of the problem, state of the art, hypothesis and general objectives.

A series of intertwined physical and biogeochemical mechanisms collectively act to keep the ocean carbon content about 50 times higher than that of the atmosphere (Sarmiento and Gruber, 2006). These mechanisms, commonly referred to as carbon pumps (Volk and Hoffert, 1985) maintain a surface-to-depth gradient of total Dissolved Inorganic Carbon (DIC, e.g. the sum of all the inorganic species of carbon in dissolved form). About 10% of this gradient is maintained by the so-called **solubility pump**: decreasing sea surface water temperature increases CO_2 solubility at high latitudes where deep water formation also occurs, resulting in an injection of carbon-rich water below the main thermocline. The remaining 90% of the DIC vertical gradient is maintained by the assimilation of carbon into organic matter (either particulate or dissolved) and minerals at the surface and its subsequent transport (via sinking, advection or mixing) into the interior of the ocean where it is remineralized back into DIC – a set of processes referred to as **Biological Carbon Pump (BCP)**. Because of the large ocean carbon reservoir, any perturbation to the ocean's capacity to absorb and store carbon has the potential to translate into a significant increase of atmospheric CO_2 content (e.g. Bernardello et al., 2014a).

As a further level of complexity, the **total ocean carbon uptake** can be considered as the sum of an **anthropogenic and a natural component**. The former refers to the extra carbon emitted by human activities since the beginning of the industrial revolution while the latter refers to the amount of carbon that was already stored in the ocean in preindustrial times. It is commonly accepted that the ocean takes up anthropogenic carbon through the solubility carbon pump while the BCP acts mostly on the natural carbon. Both components are highly uncertain, especially when considered regionally, yet the natural carbon flux has received far less attention because it is believed to be in a global steady-state. However, our limited knowledge of the mechanisms regulating the BCP does not justify this assumption. For example, global estimates of the amount of organic carbon sinking or being transported below the seasonal mixed layer (i.e. the export production, a typical measure of the strength of the BCP) vary from 5 to >12 Pg C yr^{-1} (Boyd and Trull, 2007; Henson et al., 2011). The breadth of these estimates is almost three times larger than the estimated ocean uptake of anthropogenic carbon (2.6 Pg C yr^{-1}; Le Quere et al., 2016) highlighting our limited knowledge of the present-day functioning of the BCP let alone its future response to climate change.

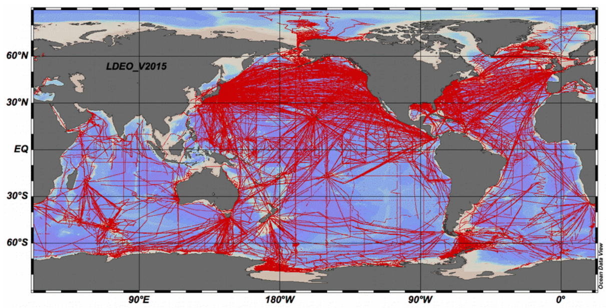

Figure 1. Distributions of pCO2 observations in the LDEO-V2015 database.

The Southern Ocean (<30º S) represents about 30% of the global ocean yet it is believed to be responsible of up to 50% of the global uptake of anthropogenic carbon (Gruber et al., 2009). However, compared to the northern portion of the oceans, this region is a data desert (Fig. 1) due to the great difficulty of obtaining observations, particularly in the wintertime, and the functioning of the BCP is especially poorly understood. As an example, besides the export production, another important measure of the strength of the BCP is the particle transfer efficiency. This is the ratio between deep (measured below 1000m) and shallow (the export production, measured at 100m depth) particle flux. Particle transfer efficiency is known to drive significantly the variability in air-sea CO_2 partitioning (Kwon et al., 2009). However, independent estimates of the spatial variability of such parameter have returned contradictory results in the Southern Ocean (Guidi et al., 2016; Marsay et al., 2015; Henson et al., 2012) leaving the carbon uptake mediated by the BCP in this region as a source of considerable uncertainty in climate projections (Kessler & Tjiputra, 2016). Although the solubility pump, rather than the BCP, is responsible for the majority of anthropogenic C uptake, the current lack of understanding in how the Southern Ocean BCP operates leads to significant uncertainties in the regional uptake of total C. These uncertainties are large enough to confound accurate projections of anthropogenic C uptake.

Dynamics regulating the carbon uptake in the Southern Ocean are extremely complex and uncertain with the net CO_2 uptake being only a small residual resulting from much larger opposite fluxes. For example, the seasonal cycles of temperature-driven CO_2 solubility and biologically-driven CO_2 uptake work in opposite phases (Takahashi et al., 2012). Additionally, the Southern Ocean is a highly dynamical environment and a major carbon pathway between the surface and the deep ocean (Russell et al., 2006). Here, the Antarctic Circumpolar Current (ACC) flows uninterrupted eastward around Antarctica driven by westerly winds. Wind-driven upwelling pulls at the surface deep water in the proximity of the ACC, delineating from south to north the southern ACC, the polar and the subantarctic fronts (Orsi et al. 1995). Because this water has been away from the contact with the atmosphere for centuries it is supersaturated in natural carbon as the result of the ubiquitous work of the BCP. As such, it tends to release CO_2 into the atmosphere. Ekman transport (i.e. to the left of the wind direction) moves this water northward where it gets warmer and its CO_2 solubility decreases, accelerating the outgassing. At the same time however, phytoplankton consume part of the DIC taking advantage of the large amount of nutrients that were upwelled together with it, favouring the uptake of more CO_2 from the atmosphere. Things are further complicated by the role of eddies that move warmer water southwards across the polar front working against the CO_2 efflux (Dufour et al., 2015).

The result is a general meridional separation (Fig. 2) where the Southern Ocean acts as a net sink of CO_2 north of the polar front while the sign of CO_2 contribution to the atmosphere on the south of the front is highly uncertain (Lenton et al., 2013). Moreover, complex patterns of water masses subduction and reventilation along the main path of the ACC result in a general zonal patchiness in CO_2 uptake that add to the overall complexity and uncertainty (Sallee et al., 2012). It is believed that, at present, the strong uptake of anthropogenic C overcompensates the outgassing of natural C resulting in a net CO_2 sink (Khatiwala et al., 2009, Gruber et al., 2009). However, recently, researchers from the SOCCOM project (http://soccom.princeton.edu/, see Section 1.4), after analysing data from BioArgo floats, have found surprisingly high winter p CO_2 in some regions of the Southern Ocean, pointing to a weaker CO_2 uptake as the net flux is proportional to the difference between air and sea surface CO_2 concentrations. This suggests that the Southern Ocean C sink could be much smaller than previously estimated (Williams et al., 2017).

Moreover, in addition to the complex physical and biogeochemical dynamics interacting in the Southern Ocean, detecting trends in carbon uptake has proven challenging because this region is also subject to strong interannual and **decadal variability**. This has contributed to confound potential trends linked to climate change (McKinley et al. 2016) and led scientists to describe first a slowdown (Le Quere et al., 2007) and then a reinvigoration of the Southern Ocean carbon sink (Landschutzer et al., 2015).

However, over the past few years, **near-term climate predictions** have emerged as rapidly improving tools at the service of society and decision-makers. The CMIP5 model experiment suite included a set of near-term climate predictions that proved skilful at regional scales (Doblas-Reyes et al., 2013). Moreover, near-term climate predictions have proven their ability to predict global-scale variability mechanisms like, for example, the recent ocean-driven hiatus in the increase of global surface temperature (Guemas et al., 2013) or the fluctuations in the strength of the North Atlantic subpolar gyre (Wouters et al., 2013). Near-term climate predictions can be performed using state-of-the-art ESMs. Producing near-term ocean biogeochemistry predictions is an emerging and promising idea but it has been applied only to two models so far, to investigate the predictability of primary production over the tropical Pacific (Seferian et al., 2014) and of carbon uptake over the North Atlantic (Li et al., 2016). Taking into account this previous attempts we formulate **the first hypothesis of this proposal:**

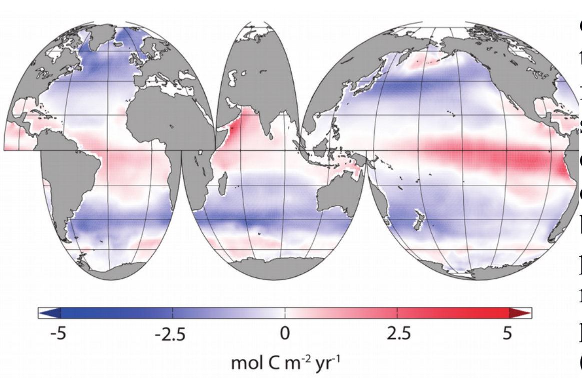

Figure 2. Climatological (1982-2011) air-sea CO2 flux (Landschutzer et al. 2015)

Despite its complexity, carbon uptake in the Southern Ocean can be predicted on seasonal-to-decadal timescales using an Earth System Model and state-of-the-art initialization techniques.

Several factors can limit the predictive capability of an ESM for C uptake. The representation of ocean and atmospheric dynamics can be negatively affected by coarse spatial resolution, inadequate subgridscale parameterizations, incomplete description of processes etc. Addressing these issues goes beyond the scope of this proposal. However, one factor that we plan to address here is the impact that the representation of the BCP has on the total carbon uptake estimate. A clean attribution of the anthropogenic carbon uptake to the solubility pump alone is not possible as **the two pumps do not work independently from each other**. In fact, although physical processes are responsible to ultimately transport anthropogenic carbon below the seasonal mixed layer it's the biological activity that determines most of the DIC vertical gradient that drives the air-sea CO_2 flux (natural+anthropogenic). As a matter of fact, the importance of biology for total carbon uptake in the Southern Ocean goes beyond the amount of carbon directly exported to the deep ocean in organic form (i.e. the export production). This is because the ocean carbon content is increasing as atmospheric CO_2 keeps growing. As a result, the ocean buffer capacity, sustained by the reaction of CO_2 in seawater, decreases making the biological consumption of carbon more effective at lowering CO_2 concentration in seawater. For example, Hauck and Volker (2015) have shown how the same amount of biological carbon drawdown by year 2100 will lead to a more than twice as large reduction in seawater CO_2 concentration than at present and hence to a larger CO_2 gradient between ocean and atmosphere that drives the gas exchange. This mechanism represents a clear example of how the uptake of anthropogenic C is ultimately regulated also by the BCP. Motivated by this we formulate **the second hypothesis of this proposal:**

A significant portion of the inter-model variability in air-sea CO_2 flux is caused by the variability in the representation of the export field. Therefore, improving the representation of biogeochemistry would improve the representation of total carbon uptake (natural+anthropogenic).

The underlying objective of the PI's main line of research is to improve the way ESMs represent ocean biogeochemical cycles, one fundamental aspect of which is ocean carbon uptake. The activities planned in this project are designed coherently with this objective and are meant to contribute to the establishment of a research group in this area within BSC. More specifically, using the EC-Earth ESM (see Section 4 for details on models and software) within this project **we propose an extensive assessment of our ability to predict the ocean carbon uptake on timescales ranging from one month to one decade ahead. Moreover, we plan to improve our understanding of how uncertainty in the carbon uptake mediated by the BCP is propagated to the total carbon uptake estimate.** To achieve these goals we focus on the Southern Ocean because of its quantitative importance in global C uptake.

1.3 Relevance for national and international strategies of research and development.

DeCUSO fits the **"Estrategia Española de Ciencia y Tecnologia y de Innovacion 2013-2020"** for multiple objectives: **Objectives 1.1 (Formación y capacitación en i+d+i) and 1.2 (Movilidad y desarrollo de la carrera investigadora)** because of its international profile and the possibilities that will be offered to the postdoctoral scientist and the doctoral student to collaborate with members of the working team who are part of recognized institutions that routinely lead large international projects. These types of collaborations are the ideal ground from where a successful career network is built.

Moreover, this project has the potential to push the Barcelona Supercomputing Center (BSC, the host institution) and Spain at the forefront of the international scientific community for ocean biogeochemistry and carbon cycle. Decadal predictions of carbon uptake are a new application of Earth System Models, one that is being explored only by two groups worldwide, so far. If funded, DeCUSO can consolidate the profile of the PI and the rest of the research team within the community, opening a direct channel to future European funding. The Climate Prediction Group (CPG) within the Earth Sciences department (BSC-ES) is already a regarded member of the international climate science community. The successful establishment of a research sub-group in ocean biogeochemistry within CPG will complete the spectrum of activities in which BSC is a reference player at the international level, making DeCUSO fit for **objective 2.6 ("Fortalecimiento institucional")**.

DeCUSO also takes on the challenge to provide society with better predictions of future near-term carbon uptake fully in line with "Reto" number 5: **"Acción sobre el cambio climático y eficiencia en la utilización de recursos y materias primas"** which corresponds to one of the challenges of H2020: **"Climate Action, Environment, Resource Efficiency and Raw Materials".** The possibility to provide reliable decadal predictions of carbon uptake will allow to reduce the cost of uncertainty in compatible CO2 emissions. Such cost is estimated here to be between 2.7 and 4.3 billion € for Spain alone (see Section 1.1). In this optic DeCUSO offers a potentially significant return on investment for the Spanish society. Furthermore, besides the knowledge, DeCUSO will generate a set of tools in form of climate modelling practices and routines that can be used to advise policy makers in planning the transition to a future sustainable post-oil energy mix, partially fitting with "Reto" number 3: **"Energía segura, eficiente y limpia"**.

Finally, DeCUSO will contribute to two of the Grand Challenges defined by the World Climate Research Program (WCRP): **"Carbon feedbacks in the climate system"** and **"Near term climate prediction"** and its results will also be used to discuss future strategies within the WCRP **working group on Subseasonal to Intedecadal Predictions**, chaired by Francisco Doblas-Reyes, head of the Earth Sciences department at BSC.

1.4 Background of the Research Team and links to other groups working in the topic.

Dr. Raffaele Bernardello (PI on this project) has a wide experience in the use and development of Earth System Models, particularly on the ocean biogeochemical aspect. During his PhD (Universitat Politecnica de Catalunya, Spain) he implemented a coupled physical-biogeochemical model configuration for the Western Mediterranean Sea to study the interannual variability of phytoplankton blooms and their relation to the export of organic matter (Bernardello et al., 2012). After the completion of his PhD he joined the Ocean and Climate Dynamics group at the University of Pennsylvania as a postdoctoral researcher under the supervision of Dr. I. Marinov. At the same time Bernardello has strictly collaborated with the Atmospheric and Oceanic Sciences department at Princeton University, led by Prof. J. Sarmiento. During this time he has directed his research at unveiling the complex mechanisms regulating the response of ocean carbon uptake to projected physical perturbations driven by future climate change using a climate model, with particular attention to Southern Ocean's dynamics (Bernardello et al., 2014a, 2014b). Bernardello then moved to the UK where he accepted a position as a research scientist within the Ocean Biogeochemistry and Ecosystem Department at the National Oceanography Centre (NOC), Southampton. At NOC Bernardello collaborated, among others, with Dr. A. Martin (part of the working team of DeCUSO) and Prof. S. Khatiwala to investigate the impact on global nutrient distributions of different parameterizations commonly used in ESMs for export and remineralization of organic matter (Bernardello et al., submitted). As part of his work at NOC, Bernardello led the adaptation of the Transport Matrix Method (Khatiwala et al., 2005) to the ocean model NEMO. This line of activity has direct ties with the work proposed in WP1 of this project where the TMM will be applied to NEMO within EC-Earth 3.2 (the climate model used at BSC). Finally, in 2017 Bernardello joined BSC as a Marie-Curie fellow.

Prof. Eric Galbraith obtained his PhD at the University of British Columbia studying past, natural changes in the carbon cycle over the ice ages using a combination of paleoclimatic observations and general circulation models. His PhD work resulted in a number of publications, including two in Nature (Galbraith et al., 2007; Schmittner and Galbraith, 2008). From 2006 to 2009 he worked as a postdoc in Jorge Sarmiento's group at Princeton University, in close collaboration with the Geophysical Fluid Dynamics Laboratory (GFDL). During this time he delved deeply into the inner workings of the GFDL models, developed a new biogeochemical model, BLING (Galbraith et al., 2010) and configured a new coarse-resolution version of the GFDL coupled climate model, CM2Mc (Galbraith et al., 2011) suitable for investigating long timescales. Galbraith then took up an assistant professorship at McGill University, where he worked from 2009-2015. He, his students and postdocs developed global data compilations and ran model simulations on a wide range of topics, including changes in ocean carbon storage and oxygenation (e.g. Jaccard and Galbraith, 2012), ocean circulation and ecosystem responses to climate warming, fish communities and fishing (Galbraith et al., 2017), and the role of zooplankton in global carbon cycling (Bianchi et al., 2013). He accepted an ICREA position in 2015 after being offered tenure at McGill, and is now based at ICTA on the UAB campus, where he is leading the ERC-funded BIGSEA project to improve the understanding of links between biogeochemistry, climate, ecosystems, and fisheries.

Dr. Valentina Sicardi, holds a Masters Degree in Environmental Sciences with majors in Oceanography and Meteorology from the Univerisita' Parthenope, Napoli, (Italy) and obtained a PhD degree from the University of Hamburg for her research at the Max Planck Institute for Biogeochemistry, Jena, (Germany). Since 2010 she has worked at the Earth Sciences Department of the Barcelona Supercomputing Center where she has developed a post-process system to assimilate data with Kalman Filter to improve statistics of air quality forecast. In 2016 she joined the Climate Prediction Group in the same department and at present she is conducting research on the optimal strategy to initialize the climate model EC-Earth for seasonal-to-decadal predictions while also contributing to the coupling of the ocean biogeochemical model PISCES to EC-Earth and the generation of initial conditions for biogeochemical predictions.

Pierre-Antoine Bretonnière, holds a Masters Degree in "Mathematical and Mechanical Modelling" from the Matmeca engineer school in Bordeaux (France). Graduated in 2010, he has worked in several climate research institutes (CERFACS -Toulouse - France, Catalan Institute of Climate Sciences - Barcelona - Spain and the Earth Sciences Department of the Barcelona Supercomputing Center). His work focuses on climate models outputs and diagnostics, data management and model coupling. He was the person in charge of the data management plan and data conventions definitions in the SPECS FP7 project and has participated in several other European projects. He is also involved in the Research Data Alliance (RDA) framework as chairman of the "Weather, climate and air quality" interest group.

Nicolau Manubens is the main developer, maintainer and coordinator of the activities related to the s2dverification R package of high performance tools for climatic data retrieval and statistical analysis since its creation 4 years ago. He holds a 5-year Computer Science degree from the Universitat Autònoma de Barcelona (UAB). He has designed and implemented web applications and associated relational databases besides contributing to database development and to several projects where he acquired programming skills in HTML, PHP, CSS, JavaScript and Python. He has experience in the use of computing nodes and scheduling systems in a GNU/LINUX environment and in bash scripting and, more deeply, in R scripting language.

In this project R. Bernardello and E. Galbraith put to service their common experience in ocean carbon cycle and Southern Ocean dynamics with the collateral benefit of maintaining an existing collaboration in this area of study. The project will count on the experience of V. Sicardi who has a background in ocean biogeochemistry and an extensive experience with EC-Earth and the in-house computing environment (Autosubmit, Earth-diagnostics, s2dverification see Section 4 for details). Furthermore, the full support from P.A. Brettoniere and N. Manubens will provide the necessary technical expertise for the variety of activities proposed.

Furthermore, as part of the working team, internationally recognized scientists Thomas Frölicher and Adrian Martin will collaborate with the postdoc and the members of the research team. T. Frölicher is an expert in ocean carbon and heat uptake and has worked, among other things, with large model ensembles and will be collaborating at the project during the analysis of decadal predictions of carbon uptake (WP2). A. Martin is an oceanographer with extensive experience on bio-physical interactions in the ocean and will provide his expertise on the activities related to the influence of the BCP on total carbon uptake (WP3).

Through existing collaborations of the PI, this project will be of interest for and will benefit from ongoing international projects:

The UK's NERC funded grant **COMICS** (Controls over Ocean Mesopelagic Interior Carbon Storage; http://www.comics.ac.uk/) is a four year collaborative research lead by NOC-OBE and involving 5 other UK institutions. COMICS aims at quantifying the flow and fate of carbon in the ocean's interior in order to model more accurately the global carbon uptake. COMICS' field activities will be focussed on two regions of the Southern Ocean. The modelling design proposed in DeCUSO is complementary to the modelling activities of COMICS as it is a natural continuation of the research line of the PI (Bernardello) who also contributed to the design of COMICS while at NOC. Furthermore, one of the co-PI's on COMICS (A. Martin) is involved in DeCUSO as a member of the working team and will be visiting BSC during the second year to analyze and discuss simulations from WP3 and compare results with those from COMICS.

The US' **SOCCOM** project (**Southern Ocean Carbon and Climate Observations and Modeling** https://soccom.princeton.edu/ **)** is a six-year initiative funded by the National Science Foundation's Division of Polar Programs. Ten prestigious american organizations are involved in SOCCOM which is headquartered at Princeton University, under the direction of Prof. J. Sarmiento. SOCCOM's mission is to drive a transformative shift in the scientific and public understanding of the role of the vast Southern Ocean in climate change and biogeochemistry through an unprecedented increase in the number of new observations and high-resolution modelling. Our project will benefit from the new set of observations generated within SOCCOM. In particular, winter observations of the air-sea CO2 flux are currently being incorporated into new reconstructions that can be used to assess the predictive skill of our simulations (WP2). On the other hand, the process-oriented type of modelling exercises proposed here (WP3) could be complementary to the extensive modeling activities of SOCCOM.

The recently approved NASA initiative **EXPORTS** (Export Processes in the Ocean from Remote Sensing, https://cce.nasa.gov/ocean_biology_biogeochemistry/exports/index.html) is a scoping study for a major NASA field campaign (Siegel et al. 2016). EXPORTS' main hypothesis is that organic carbon export from the euphotic zone and its fate within the ocean interior can be predicted knowing characteristics of the surface ocean ecosystem that are measurable with remote sensing instruments.

Our effort to better understand how uncertainty is propagated from the BCP to the total carbon uptake is complementary to the research activities that will be developed within EXPORTS as it offers a framework for future testing of newly generated export fields derived from satellite. Therefore, DeCUSO will put the PI, the postdoc scientist and the rest of the team in a position of interest for the international community that will be involved in EXPORTS.

As mentioned, the PI has active collaborations with some of the groups involved in COMICS and SOCCOM. Besides these, other international groups working in the area of ocean carbon uptake are:

- At the **Max Planck Institute for Meteorology** (https://www.mpimet.mpg.de; **Dr. Tatiana Ilyina)**
- At **Meteo France** (http://www.umr-cnrm.fr ; **Dr. Roland Seferian)**
- At the **Institute Pierre Simon Laplace** (https://www.ipsl.fr/en/ ;**Dr. Laurent Bopp**).
- At **GEOMAR** (Helmholtz Centre for Ocean Research Kiel, http://www.geomar.de; **Prof. Andreas Oschlies).**
- At the **University of Liverpool** (https://www.liverpool.ac.uk/earth-ocean-and-ecological-sciences;**Prof. Ric Williams**) .
- At **ETH Zurich (http://www.up.ethz.ch/; Prof. Nicolas Gruber)**
-At **University of Pennsylvania (https://climate.sas.upenn.edu/irina; Dr. Irina Marinov)**
-At **University of Rhode Island (http://www.gso.uri.edu/palter/URI/Publications.html; Dr. Jaime Palter)**
- At **University of Wisconsin, Madison (http://mckinley.aos.wisc.edu/; Prof. Galen McKinley)**

At the national level, the marine biogeochemisrty community can not count on any established research group focusing on global carbon uptake predictions. However, world-recognized observational scientists have developed successful research activities in ocean carbon cycle:

- The **CO_2 Group** at the **Vigo Marine Research Institute** (**CSIC,** http://oceano.iim.csic.es/ **)** counts with several high-profile researchers working on **CO_2** ocean uptake mostly from an observational point of view. The **CO_2** Group has been very active over almost two decades with fundamental contributions to the estimation of anthropogenic CO2 ocean content.
- At the **University of Las Palmas, Gran Canaria** (http://www.iocag.ulpgc.es/), **Prof. Javier Aristegui** runs a successful and internationally recognized research group on the role of the pelagic ecosystem in the global carbon cycle.
- At the **Marine Biology and Oceanography department** at the **Institute of Marine Sciences** (**CSIC**, Barcelona, http://www.icm.csic.es) researchers have dedicated their efforts to understand the role of the ocean in past climates and its link to atmospheric CO_2 (**Dr. Eva Calvo and Prof. Carles Pelejero**).

2. Challenges, Specific objectives and Methodology

To achieve the general objectives described in Section 1.2 we identify and describe three main challenges, each one being associated to a specifically designed objective and the methodology used to tackle them.

Challenge 1. The ocean biogeochemical component of Earth System Models is costly in terms of computing time, yet models need to be equilibrated in order to be compared, improved and calibrated.

Before performing historical reconstructions and near-term climate predictions with an ESM, the representation of the global carbon cycle should be equilibrated using preindustrial levels of atmospheric CO_2. This requires running a long simulation (called spin-up) of the order of at least 3000 years to allow all the relevant biogeochemical tracers to reach a steady-state solution in the interior of the ocean. ESMs are computationally demanding tools especially when run with a representation of ocean biogeochemistry as it is required for a full account of the carbon cycle. For this reason, a proper spin-up of the carbon cycle is seldom carried out by modelling groups and a variety of strategies have been pursued. As a consequence, however, most models are not fully equilibrated when used to simulate the historical and future evolution of climate caused by rising atmospheric CO_2 and the associated compatible CO_2 emissions. As pointed out by Seferian et al. (2016) this diversity in spin-up strategies prevents a proper assessment of model's performances with respect to biogeochemical fields in addition to possibly biasing estimates of climate-driven ocean carbon feedback and thus compatible CO_2 emissions.

If future ocean carbon uptake is simulated with a non-equilibrated ocean, the content of DIC will drift significantly affecting the estimate of the ocean carbon uptake. A common practice is then to account for the drift using a control simulation covering the same period of time where atmospheric CO_2 is kept at preindustrial levels. Such approach assumes that the change in oceanic DIC content due to the non-equilibrium of the preindustrial model solution and the change in oceanic DIC content due to the uptake of anthropogenic carbon are independent from each other. Recently such assumption has been questioned by Seferian et al (2016) who pointed out how the verification of this so-called "drift-correction" approach would require a specific experimental set-up consisting in the perturbation of biogeochemical fields to assess by how much the model projections would be modified. To overcome this first obstacle we have defined the **first specific objective** as:

Objective 1. To develop the capability to use an accelerated modelling technique with the Earth System Model EC-Earth (version 3.2) to achieve a rapid equilibration of biogeochemical tracers but avoiding the prohibitive cost of running the full ESM for thousands of years. Such method will promote the improvement of the representation of ocean biogeochemistry with the ultimate goal of reducing its uncertainty in the future.

Methodology: The equilibration of the biogeochemical component of an ESM is an essential prerequisite before performing any model evaluation, test or sensitivity study. The common practice to achieve a quasi steady-state is to run a simulation of at least 3000 years. Such simulation has a prohibitive cost in terms of computing resources if the full ESM is to be used. The TMM is an innovative technique and the only reliable alternative to the use of the full ESM.

The idea of the Transport Matrix Method (Khatiwala et al. 2005; Khatiwala 2007) is to represent the steady-state circulation of the ocean in a series of matrix operations that are an order of magnitude less demanding than the ESM itself in terms of computing resources. To apply this procedure, the ESM is equilibrated without the burden of the many tracers needed for the carbon cycle and from this equilibrium, the steady-state solution is used to extract transport matrices. These can then be used to drive the biogeochemical component and equilibrate the global carbon cycle in a fraction of the time it would have required if the ESM was used. We will consider a 20-year average from a control simulation performed with EC-Earth where the physical component of the model has been equilibrated under preindustrial conditions for atmospheric concentration of greenhouse gases and aerosols. Transport matrices are derived from the average transport of passive tracers arranged in chessboard-like patterns at their initial condition. Such patterns have to cover the whole ocean domain at each depth level.

The advantage of the TMM approach is that any ocean biogeochemical model can be easily (and quickly) tested and assessed against climatological observations (nitrate, phosphate, oxygen etc.) after having fully equilibrated its tracers. This allows to perform sensitivity studies, test new formulations and compare different models. The implementation of the method at BSC will require the adaptation of the TMM package to the local environment. This will provide the CPG and the EC-Earth community with a fundamental tool for all future activities related to ocean biogeochemistry. The amount of work required to achieve this objective can be divided in four tasks:

Task 1.1: Adaptation of the EC-Earth code for the application of the TMM.

Raffaele Bernardello, PhD 10%
Pierre-Antoine Bretonniere 10%

The first step will be the modification of the code of the ocean component (NEMO) in order to save for separate the explicitly and implicitly time-stepped contributions to transport. This task will be led by the PI (Bernardello) at the beginning of the project relying on his experience in applying the TMM to a different version of NEMO at his previous institution (NOC).

Task 1.2: Adaptation of the TMM scripts to the local computing environment.

Nicolau Manubens 30%
Pierre Antoine Bretonniere 60%

A set of Matlab scripts is publicly available to apply the TMM (see http://kelvin.earth.ox.ac.uk/spk/). These scripts orchestrate a series of model's simulations and process their outputs to finally compose the transport matrices. At BSC, a dedicated team of computer scientists and engineers (among them

P.A. Bretonniere and N. Manubens) manage centralized model's version control, compilation and execution environments through the continuous development of Autosubmit, a python-based tool. In order to apply the TMM to EC-Earth it will therefore be necessary to first translate and adapt the original Matlab scripts to the local python-based environment.

Task 1.3: Extraction of transport matrices from an historical simulation carried out with EC-Earth.

Postdoc, PhD 10%
Nicolau Manubens 20%

Once tasks 1.1 and 1.2 are completed, transport matrices can be extracted from any configuration of EC-Earth. As an indication, from the PI's experience at his previous institution, a grid like the one used in EC-Earth 3.2 (1 degree horizontal resolution and 75 vertical levels) should require 18 jobs with 75 tracers and 20 years long each.

Task 1.4: Set-up of environment to run simulations with transport matrices.

Pierre Antoine Bretonniere 30%

Once transport matrices have been obtained, one last effort is needed to prepare the computing environment. The code that actually executes the matrix operations makes use of the Portable, Extensible Toolkit for Scientific Computation (PETSc), a suite of routines and data-structures programmed in C language. Besides, the correct set-up of PETSc this task will include the adaptation of a number of routines developed by the PI (Bernardello) while at his previous institution. These routines include simplified biogeochemical models that will be needed to execute tasks related to the third objective. Moreover, following the same coupling scheme of these routines, the biogeochemical model of EC-Earth, PISCES (see Section 4 for details on models and software) will be coupled to this PETSc environment so to be used with the transport matrices.

Challenge 2. Carbon uptake in the Southern Ocean is regulated by complex dynamics and a marked decadal variability.

We propose to apply to carbon uptake the experience of the Climate Prediction Group at BSC on near-term (seasonal-to-decadal) climate predictions. To achieve this we define the **second specific objective as**:

Objective 2. To perform an extensive assessment of our ability to predict the ocean carbon uptake on timescales ranging from one month to one decade ahead using the EC-Earth ESM and provide the most robust estimate possible of ocean carbon uptake for the coming decade together with an accurate estimate of the associated uncertainty.

Methodology: Future near-term climate is the result of two components: a) – changes in atmospheric composition relative to radiatively active gases (including anthropogenic contribution); b) - an internally generated component that represents the natural variability of climate (Meehl et al., 2013). ESMs can be used to simulate **historical** and **future climate** by constraining the radiative forcing (component a) with a time-varying atmospheric composition based on observed data and future emission scenarios, respectively. These simulations do not attempt to phase the model internal variability with the observed natural variability of the climate (component b) and are thus useful only in a statistical sense on centennial timescales. ESMs can also produce **climate reconstructions** where, besides the radiative forcing, the natural variability is also as close as possible to the 'truth' by continuously constraining the model solution towards the observed state of the climate through sophisticated numerical techniques commonly referred to as **data assimilation**. Finally, ESMs can be used to perform **near-term climate predictions** where the radiative forcing is still constrained throughout the simulation but only the simulation's initial state is constrained towards the observed climate through data assimilation, a procedure referred to as **initialization**. The evaluation of the ability of a model and a particular initialization technique to produce skilful near-term climate predictions is normally assessed by comparing retrospective climate predictions with available observations (or reanalysis products). Retrospective climate predictions, are predictions of the past climate initialized using only contemporaneous information available at the time of starting the simulation (Doblas-Reyes et al., 2013). In this context, the expressions: **"near-term climate predictions" and "retrospective climate predictions"** are used as synonyms.

Since near-term predictions are performed with **ESMs, they can also provide predictions for ocean biogeochemistry and thus carbon uptake**. Here, we propose to move beyond the first attempts of Seferian et al. (2014) and Li et al. (2016) by using different and more sophisticated initialization techniques for the physical state of the ocean and by focusing on a key-region for global C uptake like the Southern Ocean. The work involved in this part of the project will be divided in four tasks:

Task 2.1: Generation of a Spin-up and a historical reference simulation:

Valentina Sicardi, PhD 30%

We will use the transport matrices generated for objective 1 to integrate the biogeochemical component of EC-Earth, PISCES, for 5000 years in order to reach steady state for ocean biogeochemical tracers under preindustrial atmospheric radiative forcing. At the end of this phase, we will produce a short (120 years) spin-up using EC-Earth (with PISCES) to obtain natural interannual variability while still using preindustrial conditions for atmospheric radiative forcing. Next, a historical simulation will be launched for the period 1860-present using observed atmospheric CO_2.

Task 2.2: Ocean biogeochemistry reconstruction with data assimilation for physical fields:

Valentina Sicardi, PhD 40%

An ocean biogeochemistry reconstruction for the period 1960-present will be performed using the nudging procedures described by Guemas et al. (2014) for the ocean and Jeuken et al. (1996) for the atmosphere and by using an Ensemble Kalman Filter for the sea-ice (Massonet et al., 2013). These sophisticated data-assimilation techniques are used and investigated in most activities of the CPG at BSC. By constraining physical fields we intend to provide close-to-observed forcing to PISCES assuming PISCES will respond by computing a solution for biogeochemistry that is closer to the 'truth' than when using a non-constrained forcing. As initial conditions for biogeochemical fields we will use those computed by PISCES for the historical simulation, taken at year 1960.

Task 2.3: Generation of carbon uptake predictions:

Raffaele Bernardello, PhD 20% — Thomas Frölicher, PhD
Valentina Sicardi, PhD 30%
Postdoc, PhD 20%
Nicolau Manubens 20%

Predictions will be initialized every three years from 1979 to present using Autosubmit. Initial conditions for physical and biogeochemical fields will be taken from the reconstruction produced in Task 2.2. Ten forecast years will be run with 10 members for each forecast start date. The ensemble will cover the period from 1979 to 2026.

Task 2.4: Analysis of prediction performance:

Raffaele Bernardello, PhD 10% — Thomas Frölicher, PhD
Postdoc, PhD 40%
Nicolau Manubens 30%

Computation of skill scores between the reconstruction of air-sea CO_2 fluxes by Landschutzer et al. (2015) and the set of near-term predictions. The reconstruction is available with a 1-degree surface horizontal resolution and covers the period from 1982 to 2011 with monthly averages based on a 2-step neural network technique that makes use of most available p CO_2 observations. The analysis of simulations' performance will rely on the expertise of the department to apply a wide variety of prediction scores. For example, researchers at BSC-ES develop and distribute under the direction of N. Manubens) an R package designed for forecast verification: s2dverification (= seasonal to decadal verification).

Challenge 3. Carbon pumps do not work independently.

This challenge represents a potentially important source of uncertainty in carbon predictions. We have therefore defined the **third specific objective** as:

Objective 3. To improve our understanding of how and to which degree the current uncertainty in the strength of the biological carbon pump is propagated to the estimate of the Southern Ocean carbon uptake projected by ESMs into the future.

Methodology: Because ESM's generate significantly different export fields as the result of a variety of biogeochemical model formulations, we want to quantify how much of this variability is passed onto the estimate of total carbon uptake. Using the transport matrices generated for objective 1, and taking advantage of a suite of simplified biogeochemical models already developed by the PI and adapted to be used in the local system (Task 1.4), we will perform a series of simulations where export fields derived from the control+historical simulations of models that contributed to the 5th phase of the Coupled Model Intercomparison Project (CMIP5) will be used as a forcing.

Moreover, using the same modeling protocol, we will test the consistency between export fields derived from remote sensing chlorophyll and the air-sea CO_2 flux reconstruction of Landschutzer et al. (2015), the same dataset used to evaluate predictions from Objective 2. Deriving export production from remote sensing chlorophyll requires a number of assumptions as a vertical flux needs to be derived from a combination of 2D fields. Global export fields derived with these algorithms are highly uncertain and can be very different from each other particularly in the Southern Ocean where long seasonal gaps occur in the remote sensing record due to the low light incidence and the very limited number of in-situ observations of particle fluxes during winter months. At the same time, total ocean carbon uptake has been historically quantified by measuring parameters relative to carbon chemistry at the sea surface and deriving air-sea CO_2 fluxes using bulk formulae. Although this procedure is rather precise, the coverage of the ocean surface is incomplete with the Southern Ocean standing out as a data desert during winter months. To fill these gaps sophisticated mapping techniques have been elaborated (one being Landschutzer et al. 2015, used here). These global maps of air-sea CO_2 fluxes are also affected by uncertainty and offer an estimate of the total (natural+anthropogenic) ocean carbon uptake, without discriminating between physically- and biologically-driven uptake. Considered then the global nature of these datasets and the inevitable uncertainty affecting them a logical question to be asked is if they are consistent with each other.

Because the circulation representation will be the same across simulations, the resultant differences between them in air-sea CO_2 flux will be entirely due to the different export fields.

Task 3.1: Execution of simulations with transport matrices and export fields produced by other models.

Raffaele Bernardello, PhD 20%	Adrian Martin, PhD
Eric Galbraith, PhD 20%	
Postdoc, PhD 10%	

We will select 5 models from the CMIP5 suite to cover most of the spread in air-sea CO_2 flux but at the same time making sure they have heterogeneous export fields, particularly in the meridional direction. A 5000 year spin-up for each export field will be run to equilibrate biogeochemical properties using atmospheric CO_2 levels from year 1860 and the export fields from the selected CMIP5 control simulations. Next, from each spin-up we will start a transient simulation where atmospheric carbon will evolve according to observations from 1860 to present and the export field will be the one derived from the selected CMIP5 historical simulations.

The resultant air-sea CO_2 fluxes for each model will then be compared with those produced by the original ESM. This exercise will provide an estimate of how much of the spread in ocean carbon uptake exhibited by CMIP5 models can be explained by the differences in the export fields.

Task 3.2: Execution of simulations with transport matrices and satellite-derived export fields.

Raffaele Bernardello, PhD 20%	Adrian Martin, PhD
Eric Galbraith, PhD 20%	Thomas Frölicher, PhD
Postdoc, PhD 10%	

We will test six different export fields encompassing a wide range of total global export. These fields are derived from the combination of three primary production algorithms (Marra et al., 2003; Behrenfeld and Falkowski, 1997; Carr et al., 2001) and two export algorithms (Henson et al. 2011; Dunne et al., 2005). Each simulation will be equilibrated for 5000 years so to achieve a steady-state representation of carbon chemistry. During this phase, atmospheric carbon concentration will be maintained at preindustrial levels (year 1860). Next, a transient simulation will start where atmospheric carbon will evolve according to observations from 1860 to present.

Task 3.3: Analysis of simulations from task 3.1

Raffaele Bernardello, PhD 10%	Adrian Martin, PhD
Eric Galbraith, PhD 40%	Thomas Frölicher, PhD
Postdoc, PhD 10%	

The resultant air-sea CO2 fluxes for each model will be compared to those produced by the original ESM. This exercise will provide an estimate of how much of the spread in ocean carbon uptake exhibited by CMIP5 models can be explained by the differences in the export fields. The analysis will focus on those regions of active transport of carbon below the mixed layer. We will reproduce the method of Sallee et al. (2012) to find such regions in the model. This will give us some insight into the effect of export fields in the preconditioning of these hot-spots for carbon uptake in the Southern Ocean.

Task 3.4: Analysis of simulations from task 3.2

Raffaele Bernardello, PhD 10%	Adrian Martin, PhD
Eric Galbraith, PhD 20%	Thomas Frölicher, PhD

The resultant air-sea CO_2 fluxes for each export field will be compared with the observations. However, because these simulations won't have any interannual variability (i.e. the transport matrix method only represents the average circulation) the comparison will be done between the climatological mean of the observations (1982-2011) and that of the transient simulations for the same period.

3. Implementation

DeCUSO is divided in three work packages corresponding to the three specific objectives described in Section 2. Figure 3 shows a Gantt chart for the activities proposed.

Work package 1: Set-up of transport matrix method in the local system, extraction of transport matrices from Ec-Earth 3.2. Tasks from 1.1 to 1.4. This WP will deal with the most technical part of the project where the tools needed for the rest of work packages are developed. P.A. Bretonniere and N. Manubens will lead most of the activities in this WP, supervised by the PI who has an extensive experience with the method and its implementation.

Work package 2: Production and analysis of decadal predictions of carbon uptake. Tasks from 2.1 to 2.4. This WP is meant to produce the simulations used to assess our capability to predict carbon uptake on decadal timescale. V. Sicardi will lead most activities supervised by the PI and assisted by the postdoc. T. Frolicher (working team) will participate in the set-up and analysis of the predictions. During the execution of these tasks he will visit BSC for one week. We have also budgeted one visit for either the PI or the postdoc to the University of Bern to extend the analysis of the predictions and compare them with complementary modeling exercises that Frolicher is planning on conducting with another ESM.

Work package 3: Production and analysis of simulations using external export fields from other models or satellite products. Tasks 3.1 to 3.4. This WP addresses the process-oriented part of this proposal. Here we look in detail at the processes responsible to propagate uncertainty to the estimate of total carbon uptake. These tasks will be carried out in collaboration among the postdoc, E. Galbraith and the PI. Moreover, A. Martin (working team) will be involved in both the design and the analysis of the simulations and he will be visiting BSC for one week during this period. T. Frolicher will also participate in the analysis of these results.

Deliverables

D1.1: Capability to extract transport matrices from current (and future) versions of EC-Earth.
D1.2: Transport matrices for EC-Earth 3.2 control simulation.
D1.3: Capability to use PISCES and simplified biogeochemical models with transport matrices.
D2.1: Ocean biogeochemistry preindustrial steady-state for PISCES
D2.2: Ocean biogeochemistry reconstruction for 1960-present
D2.3: Decadal predictions of carbon uptake for 1979-2026

Milestones

M1: Completion of environment set-up for using the transport matrix method
M2: Extraction of transport matrices for EC-Earth 3.2 control
M3: Completion of spin-up for ocean biogeochemistry

Risk assessment and contingency plan

The major risk involved in the execution of DeCUSO is the possible delay or failure in reaching milestone M2. The successful extraction of transport matrices from the control simulation of EC-Earth is fundamental for the execution of WP2 and WP3. Should a delay occur, one visit of either the PI or the postdoc to the UK has been budgeted. This visit would be to meet with A. Martin at NOC where the PI has successfully implemented the method with another version of the same ocean model. In the unlikely event that, after the visit, the team is still unsuccessful then Tasks 2.1 and 2.2 will be carried out using an existing off-line scheme to run PISCES with the ocean model NEMO. This scheme is significantly less efficient than the transport matrix method in terms of computational cost so the activities of WP3 would have to be reduced in terms of number of export fields used for the simulations. Alternatively, we could use existing transport matrices extracted from other ocean models.

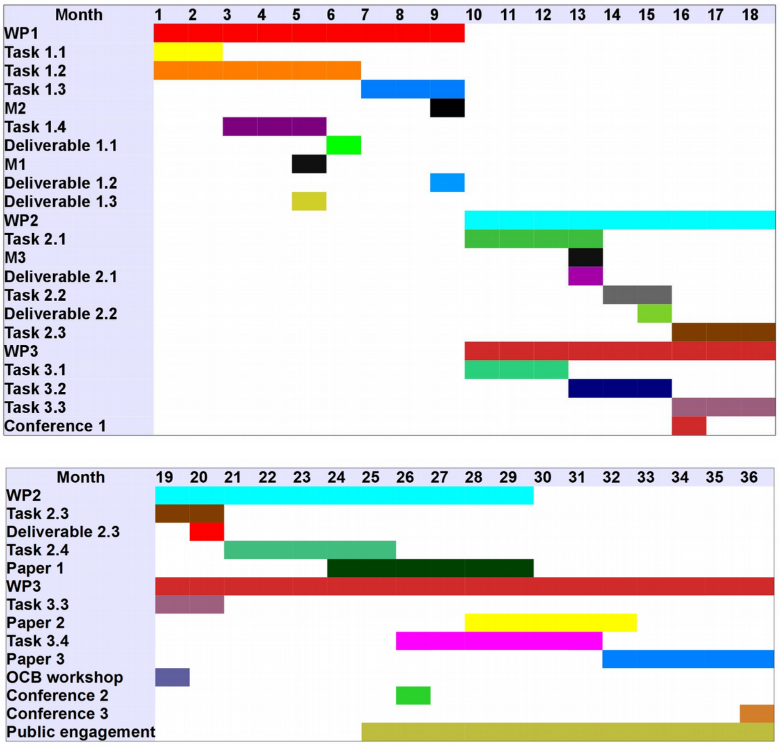

Figure 3. Calendar of activities proposed.

4. Infrastructure and technical resources.

Available hardware:

BSC is a key element of and coordinates the Spanish Supercomputing Network, which is the main framework for granting competitive HPC time to Spanish research institutions. Furthermore, BSC is one of six hosting nodes in France, Germany, Italy and Spain that form the core of the Partnership for Advanced Computing in Europe (PRACE) network. PRACE provides competitive computing time on world-class supercomputers to researchers in the 25 European member countries.

BSC operates MareNostrum, the most powerful supercomputer in Spain since its inception In March 2004. The brand new version, MareNostrum 4 was recently inaugurated during an official act that attracted the attention of the national press (La Vanguardia). MareNostrum 4 has a performance capacity of 13,7 Petaflop/s and is composed of two distinct parts. The general-purpose element, provided by Lenovo, has 48 racks with more than 3,400 nodes with next generation Intel Xeon processors and a central memory of 390 Terabytes. Its peak power is over 11 Petaflop/s, i.e. it is able to perform more than 11,000 trillion operations per second, ten times more than MareNostrum 3 despite costing only a 30% increase in energy consumption. The second element of MareNostrum 4 is formed of clusters of three different technologies that will be added and updated as they become available. These are technologies currently being developed in the USA and Japan to accelerate the arrival of the new generation of pre-exascale supercomputers. MareNostrum 4 will have a disk storage capacity exceeding 10 Petabytes and will be connected to the Big Data infrastructures of BSC, which have a total capacity of 24.6 Petabytes.

BSC has also other cutting-edge computing infrastructure based on latest available technology. Examples include FPGA boards, small clusters based on ARM SoCs, GPUs, etc. Finally, although every member of BSC have their own desk and desktop computer, all the machines are managed centrally to allow flexibility in their use such that every member of the staff can access their own personal computing environment from any workstation in the building.

Requested hardware:

The incorporation to the Climate Prediction Group of one postdoc scientist and one PhD student requires the acquisition of 2 new desktop computers (2,400€ total) to ensure that at any time each member of the group has access to a workstation. The acquisition of 2 laptops (1,600€ total) is necessary to allow continuity of work during conferences and visits to members of the research and working teams. The postdoc will visit frequently E. Galbraith at the UAB while the PhD student will spend two periods of at least three months each to visit her/his co-advisors in the UK (A. Martin) and Switzerland (T. Frolicher).

To store all the climate simulation outputs that will be produced during DeCUSO the storage system of the department will have to be expanded. For the amount of data that the project is expected to generate, we need around 60TB of raw space. That will require the acquisition of 1 JBOD disk cabinet which costs about 6,000 € and 15 4TB disks which cost 220€ each. The total cost of requested hardware is 9,300€.

Available models, datasets and software:

Models: Most of the simulations proposed in DeCUSO will be carried out using the Earth System Model EC-Earth (https://www.ec-earth.org/). This model is developed and maintained by a consortium of 27 research institutes from 10 European countries. The Climate Prediction Group at BSC is an important member of this consortium making fundamental contributions to the development of the model in several aspects like the representation of the carbon cycle, ocean parameterizations, computing performance etc. EC-Earth contributed and will contribute to the 5^{th} and 6^{th} phases (respectively) of the Coupled Model Intercomparison Project (CMIP5 and CMIP6) which bring together all the models that will be used to redact the reports of the Intergovernmental Panel on Climate Change. Ocean dynamics are solved by the Nucleus for European Modeling of the Ocean (NEMO), a state-of-the-art modeling framework of ocean related engines (Madec, 2008). The ocean biogeochemical component is the Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2 (PISCES-v2, Aumont et al., 2015). PISCES-v2 simulates the lower trophic levels of marine ecosystems (phytoplankton, microzooplankton and mesozooplankton) and the biogeochemical cycles of carbon and of the main nutrients (P, N, Fe, and Si).

For WP3, DeCUSO can count on the availability of already existing simplified biogeochemical models that were elaborated by the PI while at his previous institution, in collaboration with A. Martin (working team). Briefly, an ocean biogeochemical model (like PISCES-v2) is formed by state variables representing the main pools of organic and inorganic forms of a given nutrient. The model formulation allows for fluxes of mass between these pools according to semi-empirical formulations. Part of these formulations can be ignored by forcing the model to use an external source for a given field. In our case, the amount of organic particles sinking into the interior of the ocean (the export field) is read from an external source (either another model or satellite) instead of being computed by the model itself. The rest of the formulations will still work normally but the solution will adapt to the new export field.

Datasets : The datasets used for the atmospheric and oceanic data-assimilation and initialization will be reanalyses from the ECMWF (European Center for medium Range Weather Forecasts): ORAS4 and ERA40 / ERA-interim or newer if available when the project starts (ex: ERA5 expected for Spring 2018). Observed sea ice concentration and sea ice drift will be prescribed from OSISAF and ESA-CCI datasets or from a newer product if available. An independent dataset used for validation of SST will be the NOAA (National Oceanic and Atmospheric Administration) ERSSTv3b 30. Export fields to force the idealized models of WP3 will be derived by combinations of three estimates of primary production derived from different algorithms (the Vertically Generalized Production Model, the Eppley-VGPM and the one proposed by Marra et al. 2003). These algorithms use remote sensing chlorophyll derived from NASA sensors SeaWiFS (1997-2008) and MODIS-Aqua (2002-present) and they will be combined with the algorithms by Dunne et al. 2005 and Henson et al., 2011. Finally, air-sea CO2 fluxes resulting from models will be validated using the reconstruction by Landschutzer et al. (2015) that covers the period 1982-2011 at 1° grid resolution.

Software: the Computational Earth Sciences group at BSC-ES (among them P.A. Bretonniere and N. Manubens, members of DeCUSO research team) are responsible for maintaining and developing three packages that will be used in DeCUSO: 1) **Autosubmit:** a python-based tool to create and manage weather and climate experiments in diverse supercomputing environments. 2) **s2dverification:** an R package of high performance tools for climatic data retrieval and statistical analysis. 3) **Earth diagnostics:** a set of python tools to post-process model's output.

5. Human resources

Available human resources:

The DeCUSO project will be carried out within the **Climate Prediction Group (CPG)** of the Earth Sciences Department at the Barcelona Supercomputing Center (BSC-ES). CPG is composed by 14 research scientists and 3 students and it receives IT support from the **Computational Earth Sciences Group (CESG)** in the same department. Members of CESG have a highly qualified technical expertise to deal with complex parallelized codes such as the ones that will be used within this project. Besides, all members of both groups work with freely available software developing post-processing and diagnostic tools that are openly shared under GNU licenses with the rest of the community, strengthening the efficiency and impact of the work developed. They also maintain a common data repository to ensure that the research carried out makes use of the latest, highest quality observational datasets. Thanks to the host infrastructures and the strict collaboration between CPG and CESG DeCUSO can count on a unique combination of human resources with a ratio of one technician for every two researchers. Furthermore, BSC has dedicated **Communication** and **Project dissemination units** (10 staff members) that will provide assistance with outreach activities, publication of results and transfer of knowledge. Also DeCUSO's team will interact with the **Earth System Services group** to explore possible outlets of results outside the scientific community.

Requested human resources:

To achieve the ambitious objectives of DeCUSO, its team would need to contract a postdoctoral scientist for 3 years. He/she will be advised by Raffaele Bernardello, PI of DeCUSO. The postdoctoral scientist will be involved in all phases of the project particularly in the generation and analysis of decadal predictions (WP2) where he/she will strictly collaborate with T. Frolicher. The postdoc will also carry out most of the simulations of Objective 3 under the supervision of Eric Galbraith and will participate in the analysis and interpretation of results. The postdoc scientist will be encouraged to lead two of the three papers expected to be generated within DeCUSO.

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C.2. IMPACTO ESPERADO DE LOS RESULTADOS

Social/economic impact:

DeCUSO has the potential to reduce the uncertainty in the estimate of CO2 compatible emissions by improving the capability of BSC to perform skillfull decadal predictions of carbon uptake. Such capability is a fundamental asset for policy makers as governments are debating at present how to implement quinquennial plans to meet targets agreed at the COP21 Paris meeting. Because 5 years is within the lifespan of a political career, potentially unpopular measures aimed at reducing emissions (like shutting down thermal power plants, or introducing new carbon taxes) need to be backed by reassurance from the climate community that they will be effective. Results will have to be usable towards the public opinion to demonstrate the effectiveness of such measures in terms of stabilization of atmospheric CO2.

Moreover, being able to provide reliable decadal predictions of carbon uptake translates into a reduction of the cost of uncertainty in compatible CO2 emissions. Such cost is estimated here to be between 2.7 and 4.3 billion € for Spain alone (see Section 1.1). In this sense DeCUSO offers a potentially significant return on investment for the Spanish society. Furthermore, DeCUSO will generate a set of tools in form of climate modelling practices and routines that can be used to continuously advise policy makers in planning the transition to a future sustainable post-oil energy mix.

At present, besides BSC only two institutions world-wide (MPI and Meteo France, see Section 1.3) have the capability and the know-how to perform decadal predictions of carbon uptake. This places BSC and Spain in a strategic position at the forefront of the international climate science community. DeCUSO will contribute to enhance Spain's role within the EU as plans of emission regulation will be decided organically within the union.

Scientific impact:

Alongside with providing an assessment of our current capability in predicting carbon uptake on decadal timescales (WP2), DeCUSO will also highlight which specific processes are responsible for propagating uncertainty from the BCP to the final air-sea CO2 flux (WP3). This will offer the international climate science community valuable indications on which processes should be given priority in the ever-going effort of improving ESMs. From an institutional strategic point of view, at the national level, the scientific community is lacking a research group dedicated to modeling the global carbon cycle. DeCUSO is meant to sustain the PI's efforts in establishing a permanent and successful group focused on global carbon cycle predictions. At the international level, within the EC-Earth community carbon cycle activities are also being carried out without a clear coordination and lacking a leadership. If funded, DeCUSO will help the PI and BSC to become the natural reference for the carbon cycle within the EC-Earth community.

Dissemination and Internationalization of results:

At least three manuscripts will be submitted to international journals, of high-impact whenever possible. Being the outcome of public research activity, results will not be subject to commercial use. Instead, results will be widely presented in scientific conferences (e.g. Ocean Sciences, AGU and EGU general assemblies). Frequent video-conferences will be organized with our national and international collaborators to discuss results and to plan future collaborations. The results of DeCUSO will feature at meetings of the Working Group on Subseasonal to Interdecadal Prediction (part of WCRP, see Section C1-1.3), which is chaired by Francisco Doblas-Reyes, head of the Earth Sciences Department at BSC. They will also contribute to the 'Near term Climate Prediction' and 'Carbon feedbacks in the climate system' WCRP Grand Challenges through the membership of Virginie Guemas, head of the climate prediction group, in the Scientific Steering Group of CLIVAR.

Communication and popularization of science:

To respond to the demand of the general public on information about global warming, what changes to expect in the near-term and how to mitigate their effects, we will organize at least two presentations intended to non-specialists, as already done by our group in the past (e.g. V. Guemas on Artic Sea-Ice retreat at a local public library). Results from DeCUSO will also be accessible through our group website. Moreover, members of the Climate Prediction Group often receive extensive press coverage in national and international journals (e.g. El Periodico, Scientific American, La Vanguardia) also thank to a dedicated Communication Unit at BSC that is responsible for media relations, digital communication including the BSC website and social media. DeCUSO will benefit from the experience of this unit and the ever expanding network being created with members of the press, TV and radio dedicated to the general public.

Transfer of results:

The project deliverables will be shared with AEMET, which is the natural user of the climate forecast information at the Spanish level, to keep them informed about the progress of this sort of predictions. Furthermore, although a specific transfer of knowledge is not planned at this stage, BSC can count on the Earth System Services group which is dedicated to bridge the gap between climate information and end users in key sectors of society (energy, urban development, infrastructure, transport, health and agriculture) via tailored services to societal actors. They develop these services in collaboration with public administrations, private companies, funding agencies and spin-off companies that could exploit operational opportunities. DeCUSO will count on the expertise of this group to explore any possible way to exploit the results generated.

C.3. CAPACIDAD FORMATIVA DEL EQUIPO SOLICITANTE

Training program:

In the context of this project a PhD student will be recruited and will enrol in one of two doctoral programs of the Technical University of Catalonia (UPC):

1) Environmental Engineering (https://doctorat.upc.edu/ca/programes/enginyeria-ambiental), recognized with MEC Excellence Mention from 2004 to 2013 (MCD2004-00394, MEE2011-0335), and it is currently registered in the VERIFICA process of the ANECA evaluation agency (RUCT: 5600080).
2) Marine Sciences (https://doctorat.upc.edu/ca/programes/ciencies-mar), recognized with MEC Excellence Mention from 2003 to 2013 (MCD2003-00141, MEE2011-0703).

The PhD student will be supervised by R. Bernardello (PI on this project) and co-supervised by A. Martin and T. Frolicher, both members of the working team. With this arrangement the student will have the opportunity to visit for a period of three months each one of the two co-supervisors at their respective institutions (National Oceanography Centre, Southampton, UK and the University of Bern, Switzerland). Both institutions have a long and successful record of mentoring students within vibrant academic programs like the Graduate School of the National Oceanography Centre Southampton and the Graduate School of Climate Sciences at U. Bern. These visits will be arranged, when possible, coinciding with courses given at these institutions that could complement the preparation offered by the UPC.

The research theme proposed to the student will build upon and expanding the knowledge and results generated in DeCUSO. The ideal theme of research would be related to WP3 where using the tools generated in WP1 the student could explore the potential of these idealized models to design new experiments and tests new hypothesis about the interaction between carbon pumps. The theme proposed will develop around two main questions:

1- What is the role of the biological carbon pump in the preconditioning of the ocean surface pCO_2 in regions of intense carbon uptake in the Southern Ocean?

Sallee et al. (2012) showed how the transport of anthropogenic carbon away from the mixed layer in the Southern Ocean is the result of a complex series of interactions between Ekman transport, mean flow and eddy-induced transport with an overall patchy distribution that highlights areas of net subduction and areas of re-ventilation. Carbon assimilation by phytoplankton can reduce pCO_2 in re-ventilated waters mitigating the outgassing of CO_2. On the other hand, regions of net subduction could interest water that has seen recent carbon uptake and could be rich in organic matter. The modelling activities of the PhD research will be aimed at assessing how important are the meridional and zonal distributions of biological carbon uptake in this context.

2- How important is the relative timing between primary production and water masses subduction in determining the net CO_2 uptake of the Southern Ocean?

For the first question the spatial interaction between regions of favorable physical transport and primary production is described. The same reasoning can be applied for temporal variability as both processes have their own seasonal cycle. Primary production phenology (i.e. the study of plant and animal life cycles) in the Southern Ocean is characterized by marked interannual variability associated to main climate modes of variability which are also likely to affect the transport mechanisms described by Sallee et al. (2012). It is currently unknown how these cycles interact together and how the Southern Ocean carbon uptake is sensitive to relative shifts due to interannual variability and future climate change.

Throughout the duration of the PhD, the student will have the opportunity to share the results of her/his research in different national and international scientific forums and will be encouraged to co-author scientific research articles of high impact, as well as to contribute to outreach activities (see Section C2). Complementary skills required for efficient research execution and communication will be fostered through the student participation on multiple training activities offered both by BSC and UPC. Additionally, BSC has a specialized **Education and Training Unit**, dedicated to develop a curriculum based on cutting-edge scientific research on software tools for HPC and application areas. BSC-ES is directly involved on those activities and encourages all members to attend and/or contribute, including the annual edition of the course “Earth Sciences Simulation Environments at BSC”, funded by the “Partnership for Advance Computing in Europe” – PRACE- network, or the BSC Doctoral Symposia. 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, recognizing the alignment of its human resources policies to the principles set out in the EU Charter and Code for Research, thus the existence of a stimulating and favorable working environment for researchers.

Selected Previous PhD students in the group (last 5 years):

1. **Víctor Manuel Valverde Morales**. "Characterization of atmospheric pollution dynamics in Spain by means of air quality modelling". 08/04/2016. Publications: Valverde et al. (2015, Int. J. Clim.); Valverde et al. (2016a, 2016b, Sci.Total Env.).
2. **Robert Banks**. "Assessment of planetary boundary-layer schemes with advanced remote sensing instruments and air quality modelling". 04/04/2016. Publications: Banks et al. (2015, Bound.-lay. Meteorol.); Banks and Baldasano (2016, Sci.Total Env.); Banks et al. (2016, Atm. Res.)
3. **Luis Lage Rodrigues**. “Calibration and combination of seasonal climate predictions in tropical and extratropical regions”. 22/01/2016. Publications: Lage Rodrigues et al. (2014, Clim. Dyn.); Lage Rodrigues et al. (2014, J. Geophys. Res. Atm.);
4. **Michele Spada.** "Development and implementation of a fully coupled global aerosol model within the chemical non-hydrostatic multiscale model (NMMB/BSC-CHEM)”. 23/11/2015. Publications: Spada et al. (2013, Atm.Chem.Phys.); Spada et al. (2015, Atm. Env.)
5. **Danila Volpi**. “Benefits and drawbacks of different initialization techniques in global dynamical climate predictions”. 01/03/2015. Publications: Volpi et al. (2017a, Clim. Dyn.); Volpi et al. (2017b, Clim. Dyn.); Carrassi et al. (2016, Clim. Dyn.); Carrassi et al. (2014, Nonl. Proc. In Geophys.);
6. **Alba Badia Moragas**. "Implementation and development of a gas-phase chemical mechanism within the global/regional atmospheric model chemical non-non-hydrostatic multiscale model

(NMMB/BSC-CHEM)". 12/12/2014. Publications: Badia and Jorba (2015, Atm. Env.); Badia et al. (2017, Geosc. Model Dev.).
7. **Karsten Haustein**."Development of an atmospheric modeling system for regional and global mineral dust prediction". 31/01/2012. Publications: Haustein et al. (2012, Atm. Chem. Phys)

Current PhD students:
1. **Lluís Vendrell Miquel**. "Evaluation and development of an atmospheric modelling system for different spatial scales within the Dust Non-hydrostatic Multiscale Model NMMB-DUST". Expected date: October 2017.
2. **Vicenzo Obiso**. "Aerosol interaction with meteorology". Expected date: December 2017.
3. **Rubén Cruz García**. "Regional sea-ice predictability and prediction on seasonal to interannual timescales" Expected date: July 2018.
4. **Verónica Torralba**. "Seasonal climate prediction for the wind energy sector: methods and tools for the development of a climate service". Expected date: November 2018.
5. **Jaime Pérez Benavides**. "Development and evaluation of an air quality modelling system over Barcelona: from regional to street scale". Expected date: July 2019.
6. **Daniel Rodríguez Rey**. "Climate Change: climate prediction. Different time scales and from regional to global" Expected date: July 2020.
7. **Bianca Mezzina**. "ENSO influence on the North Atlantic-European winter: mechanisms and implications for predictability". Expected date: November 2020

Scientific and professional development of previous students:

Former postdocs and Ph.D. students hosted at the ES-BSC hold/have held positions in several well-known scientific institutions and energy companies around the globe, such as the NASA Goddard Institute for Space Studies in USA (Dr. Carlos Përez García-Pando, now back at BSC with AXA chair on Atmospheric composition), the School of Geography and Environment at the Unversity of Oxford in UK (Dr. Karsten Haustein) and EnBW Energie Baden-Württemberg AG in Germany (Dr. Matthias Piot). Danila Volpi currently has 5 articles accepted, 1 submitted and 1 in preparation. She has a postdoctoral position at Meteo-France on seasonal forecast quality assessment and the role of teleconnection on forecast skill. Luis Ricardo Lage Rodrigues currently has a permanent position as a research assistant at the Center for Earth System Sciences (CCST) from the Brazilian National Institute for Space Research (INPE) on the validation of climate models.

Scientific and formative context:

The Earth Sciences department at BSC (BSC-ES) conducts multi-facet research in Earth system modelling. Established in 2006, the initial core activity was focused on atmospheric composition modelling. The designation of Prof Francisco J. Doblas-Reyes as Director of the BSC-ES in 2014 initiated the merging of the BSC-ES with the Climate Forecasting Unit of the Institut Català de Ciències del Clima (IC3-CFU), which he was leading at the time and who had become in a short time a main European actor in the development of climate predictions and climate services. The newly merged department is structured around four groups with more than 50 employees, including technical and support staff. Among its members there are several national and international talented researchers who obtained funding through highly competitive programs such as: Marie Skłodowska-Curie Actions Individual Fellowships (5), Ramón y Cajal (3), Juan de la Cierva (6).

It is a highly productive scientific entity that has published more than 150 research articles in peer-reviewed journals over the last 5 years, including 5 in prestigious high-impact journals and with a very dense international collaborative network counting at least 50 institutes worldwide.

During last 5 years (2012-2016), BSC-ES was granted 9 EU H2020 projects, 5 EU FP7 projects, 5 EU Copernicus projects, 7 projects funded by the Ministerio de Economía y Competitividad (MINECO), 2 projects funded by the European Space Agency, 1 project funded by the French Ministry of Sciences and 1 project from ERA-NET. During that same period, BSC-ES also participated in 21 RES and 4 PRACE projects. BSC has been awarded with the Severo Ochoa's Centre of Excellence project of the Spanish government since its first call (2011). BSC-ES international activity includes the coordination of the two World Meteorological Organisation (WMO) regional centres specialised in sand and dust warning and forecasting, as well as the participation in climate services initiatives like the Climate Services Partnership (CSP). Members of BSC-ES participate in committees of the World Climate Research Programme (WCRP), such as the CLIVAR Scientific Steering Group or the Working Group on Subseasonal to Interdecadal Prediction (WGSIP).

C.4. IMPLICACIONES ÉTICAS Y/O DE BIOSEGURIDAD