Statement of Changes

Date	Change Description	Page or Section
14/02/2019	Timing of sub-tasks added to WP descriptions	Part A
	Timing of deliverables and milestones reworked and new intermediate deliverables added in line with PO advice	Part A
	Inclusion in WP5 of 4-monthly tele-conferences including the project coordinator and the EC EASME PO, shortly after each EB meeting in order to discuss the progress and main planned events. Minutes of the EB meeting will be shared with the PO before these tele-conferences.	Part A
	Amended mitigation for risk associated with WP2	Part A
	Removed list of participants; tables 3.1a, 3.1b and 3.1c from Section 3.1; tables 3.2a and 3.2b from section 3.2; table 3.4a from section 3.4 and entered data into part A as required	Part B
	Merged parts 1-3 with parts 4-5 to create new Annex 1 Part B	Part B
	Updated table of contents	Part B
	Split table 1.1 into table 1.1a (available existing data) and 1.1b (new or updated data) and altered references in document where necessary	pp14-15
	References to new WP6 covering ethics included where appropriate	pp17, 19, 35, 41
	Reference to using a process-based approach to emergent constraints in WP3 outlined in a recent paper (Eyring et al., 2019, *Nature Climate Change*)	p18
	Section 2.2.1 dissemination and section 3.3 consortium as a whole: note that CCICC will communicate with VERIFY, CONSTRAIN and other projects funded under the same call as CCICC and report this to the EASME PO on a 4-monthly basis	p30 and p43
	Updated research data management section referring to data storage and to the creation and updating of a Data Management Plan as a deliverable	p32
	Updated Gantt Chart split over 2 pages with WP tasks and subtasks length, timing of deliverables and milestones, and tentative timing of annual meetings. Timing of key stakeholders activities is also given	p36-37
	Updated third parties section to account for use of third parties by ENS and BSC	pp71-2
	Updated ethics section to take account of ethics review findings	p73
	Task 1.3.2 removal of model TOPAZ (GFDL-ESM) from the list	Part A
	Task 4.1.3 added reference to communications with other projects	Part A
	T4.4.3 added reference to communications plan deliverables	Part A
	T5.1 added action to feedback from EAB to EB and to EC via telecons, minutes or periodic reports and updated info on objectives to be published on website, and action to organise Kick-off Meeting and share minutes with PO	Part A
	T5.2 added action to feedback from EAB to EC and reviewers via minutes or periodic reports	Part A
	Amended PMs for ENS/CNRS in WPs 1 and 2	Part A
	Clarification of collaboration with other projects	pp30-31
	Further detail on DMP	p32
	Added CNRS role for partner ENS, including estimated time and financial allocations and added estimate time and financial allocation for ICREA resources for partner BSC in Table 4.2.	p71
	Amended partner description for CEA.	p68
	Changed status of deliverables 1.2, 1.4, 1.11, 1.12, 2.6, 3.2, 3.4 and 3.6 from PU to CO	Part A
06/01/2020	Changed the acronym CCiCC to the acronym 4C	Part A and B
	Changed the title from ‘Climate-Carbon Interactions in the Coming Century’ to ‘Climate-Carbon Interactions in the Current Century'	Part A

	Change of Leader for Deliverable D4.5 and Task 4.4.2 (Development and Curation of the Website) from UNEXE to BSC, with an adjustment of budget from UNEXE to BSC and an increase of 6.75 PMs for BSC in WP4.	Part A

Table of Contents

1 Excellence

1.1 Objectives

Climate-carbon feedbacks are leading-order uncertainties in climate projections and in estimates of the total carbon budget consistent with the goal to limit global warming set out in the Paris Agreement. 4C (Carbon Cycle Interactions in the Current Century) will advance our quantitative understanding of climate-carbon interactions and resolve large and persistent knowledge gaps in the climate sensitivity to carbon dioxide emissions. 4C will achieve its objectives through the innovative integration of new models and a wide range of observations. It will develop systems for new climate predictions and projections from annual to centennial timescales that are informed by observations, and provide key knowledge to underpin IPCC assessments and support policy makers.

1.1.1 Context

Based on recent advances in Earth system modelling, the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5) concluded that "*Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond*", unambiguously identifying the causal link between anthropogenic emissions of carbon dioxide (CO_2) and global warming[1]. The IPCC AR5 further summarized that "*Cumulative total emissions of CO_2 and global mean surface temperature response are approximately linearly related. Any given level of warming is associated with a range of cumulative CO_2 emissions, and therefore, e.g. higher emissions in earlier decades imply lower emissions later.*" The IPCC AR5 also assessed the positive feedback between climate change and the carbon cycle stating: "*there is high confidence that the feedback between climate and the carbon cycle is positive in the 21st century. As a result more of the emitted anthropogenic CO_2 will remain in the atmosphere*"[1]. These findings highlight the central role of the carbon cycle in the global climate system.

4C will advance three interlinked areas of carbon cycle research:

a) Develop a better understanding

Over the historical period, since 1750, human activities are estimated to have released about 650 GtC (1 GtC=10^{12} kgC), with about two-thirds coming from fossil fuel combustion and one-third from land-use changes[2]. Over the same period, atmospheric CO_2 concentration increased by about 50%, from about 280ppm (parts per million) to 410ppm today. The atmospheric CO_2 increase accounts for less than half of the CO_2 emitted by human activities because a large fraction of the CO_2 emissions is being absorbed by the land and the ocean (Figure 1). The main driver of these long-term land and ocean carbon sinks is the atmospheric CO_2 increase itself. Higher atmospheric CO_2 concentration leads to increased photosynthesis on land and greater CO_2 uptake by the surface ocean and transport to deeper layers. These CO_2-induced land and ocean carbon sinks can be seen as strong negative feedbacks operating on the climate-carbon cycle system. However, warming and other changes in climate induced by the atmospheric CO_2 increase (along with changes in other radiative forcers such as CH_4, N_2O and aerosols) also impact these carbon sinks[3,4]. Although CO_2-carbon cycle and climate-carbon cycle feedbacks have been identified for more than a decade[5-7], our ability to quantify them has remained limited[8,9], as is our capability to confidently attribute past changes of the carbon cycle and hence to anticipate its future evolution[10,11]. **There is an urgent need to better understand and better model the processes that drive the observed variability in atmospheric CO_2 at seasonal to century time-scales, in order to improve climate projections and inform climate mitigation and adaptation.**

b) Provide policy relevant near-term predictions

Under Article 4 of the Paris Agreement, Parties "*aim to reach global peaking of greenhouse gas emissions as soon as possible*" and to "*undertake rapid reductions thereafter in accordance with the best available science*". Hence the first major global milestone in the implementation of the Paris Agreement is for emissions to reach a peak and start decreasing. Under scenarios meeting the long-term temperature goal, this must occur within or near the timescale of this project. Identifying whether emissions have peaked is both a detection and a prediction challenge: emissions must be observed to fall, and predicted to continue to do so. Given current uncertainties in our understanding of the carbon cycle, the "*best available science*" at present would be unable to detect with confidence that emissions have peaked until one decade or more after they had actually done so (Figure 2). Reducing this uncertainty is an essential contribution of 4C to the UNFCCC global stocktake process integral to the implementation of the Paris Agreement. So far, there has been little attempt by the scientific community to predict the near-term evolution of the carbon cycle, and in particular what would be the near-term growth rate of atmospheric CO_2 in the next decade if all countries follow their Paris agreement ambitions on emissions reduction. **There is an urgent need to develop the capability to simulate and assess**

the near-term evolution of the global carbon cycle and the climate system in response to different near-term emission trajectories.

c) Reduce long-term projections uncertainties for policy-making

The Transient Climate Response to Cumulative Carbon Emissions (TCRE) is the Earth system metric that quantifies the global average surface warming for a given cumulative emission of CO_2 (1000 GtC) and can be used to infer the carbon emissions consistent with a given climate target[12,13]. TCRE is an attractive metric for policymakers as it directly links CO_2 emissions to global warming. While individual Earth system models reveal a nearly linear relationship between global warming and cumulative carbon emissions, the allowable carbon emissions for a global warming target, such as the 2°C target, are poorly constrained (Figure 3), and the uncertainties are currently too large to be useful for international climate negotiations. The uncertainty in carbon cycle feedbacks is as large as the uncertainty arising from physical climate feedbacks alone[14], it severely undermines attempts to estimate the climate response for a chosen emission scenario, and similarly, to quantify the anthropogenic CO_2 emissions that would be consistent with a stabilization of global warming at a chosen level. Resolving key carbon cycle uncertainties, in particular for stringent mitigation scenarios, is essential in order to provide greater clarity on necessary mitigation actions required to meet the Paris Agreement Long-Term Temperature Goal (LTTG) of "limiting warming to well below 2°C, and pursuing efforts to 1.5°C", hence limiting the effects of dangerous climate change. **There is an urgent need to provide useful constraints on TCRE to inform policy-making.**

4C has three overall scientific objectives to tackle persistent knowledge gaps in climate science, all supporting a fourth objective of knowledge transfer. 4C will achieve its scientific objectives, using new observations and observational techniques, together with enhanced process understanding and new improvements in Earth system modelling for better understanding past and anticipating future changes.

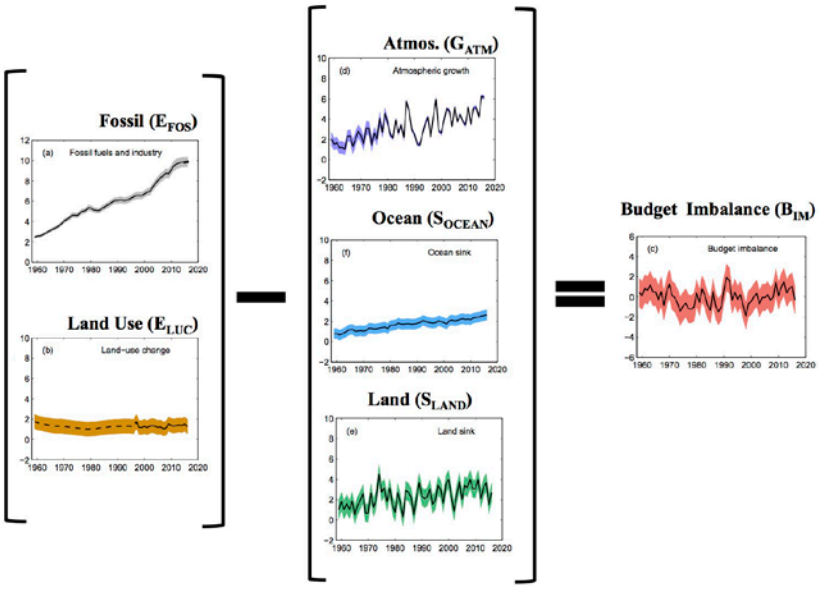
1.1.2 Overall objective 1: Better understanding of processes controlling the global carbon cycle

Overall objective 1 of 4C is to make a major improvement in our understanding of the global carbon cycle over the historical period, by producing a comprehensive set of novel constraints using innovative methods and new observations, and applying these new constraints to critically assess and improve current carbon cycle models.

The conventional approach to quantify global carbon emissions and their partitioning among the environment, so called the 'global carbon budget'[2], including by the IPCC[15], relies on estimates of fossil fuel emissions (E_{FF}) and land-use change (E_{LUC}) derived from a combination of national reporting and bookkeeping modelling; observed atmospheric CO_2 increase (G_{ATM}); and ocean CO_2 uptake estimates (S_{OCEAN}) from either global ocean circulation-biogeochemistry models when annual estimates have been provided, or from indirect estimates based on ocean observations when only decadal means were needed. The land sink (S_{LAND}) is then estimated as the residual term needed to close the global carbon budget ($S_{LAND} = E_{FF} + E_{LUC} - (G_{ATM}+S_{OCEAN})$). For more than thirty years, the land carbon balance has been estimated with this method, as a residual of the global carbon budget[16,17]. Because this approach assumes that the global carbon budget is perfectly closed, it precludes the opportunity to objectively test our understanding of the global carbon cycle. Even the IPCC AR5 did not quantify individually, using independent estimates, all five components of the historical global carbon budget[15], which constitutes a major limitation. Furthermore, recent estimates of the oceanic sink S_{OCEAN}, based on ocean surface pCO_2 observations have suggested that the interannual to decadal variability in the ocean carbon sink could be as much as 2-5 times larger than generated by ocean carbon cycle models[18]. Having a potentially large missing variability in ocean uptake estimates implies that deriving S_{LAND} from the carbon budget residual is no longer tenable.

In 2017, the Global Carbon Project (GCP), led by several 4C project partners, assessed for the first time each term of the global carbon budget independently, with an estimate of the land sink (S_{LAND}) based on an ensemble of land carbon cycle models[2]. This new approach allows quantifying the carbon budget imbalance ($B_{IM} = E_{FF} + E_{LUC} - (G_{ATM}+S_{OCEAN}+S_{LAND})$). B_{IM} is a measure of imperfect closure of the global carbon budget and hence it offers a quantitative measure of the community's level of understanding of the contemporary carbon budget. The B_{IM} shows annual absolute errors of 0.7 $GtCyr^{-1}$ on average, with large year-to-year variability of 1-2 $GtCyr^{-1}$ (corresponding to 10-40% of fossil emissions), and also longer, semi-decadal anomalies of 0.5-1 $GtCyr^{-1}$ (Figure 1). The B_{IM} does not show any clear bias, with both long-term mean and the trend close to zero. Given the very low year-to year variability in anthropogenic emissions[19], we expect the B_{IM} variability to be primarily due to errors in the understanding of processes driving land and ocean carbon sinks, and their responses to climate variability, as represented in models. For example, we suspect that the large imbalance in the early 1990s could be due to the poor representation of the climate impact of the Mount Pinatubo volcano on ecosystems in land carbon models[20,21]. The sustained negative B_{IM} in the 1970s (too large sinks) could similarly be caused by the yet to be explained large land sink over that period, while the positive B_{IM} in the late 2000s (too weak sinks), and possibly also in the 1960s, could be due to an underestimation in models of the ocean sink variability in the Southern Ocean[22]. We will work to significantly reduce the B_{IM} in 4C.

Figure 1. *Global carbon budget over the Mauna Loa period (1959-2017), showing the CO_2 emissions from fossil fuels and industry and from land-use and land cover changes (two left panels); their storage in the*



atmosphere and the ocean and land carbon sinks (three middle panels); and the residual carbon budget imbalance (right panel). Units $GtCyr^{-1}$(adapted from Le Quéré et al 2018).

Recent Earth observations and new data-driven products provide multiple opportunities to evaluate and constrain current models in order to significantly reduce the B_{IM} over the entire historical period. However, identifying and synthesizing the most relevant constraints within a global budget approach (rather than on the basis of individual components) requires a strong and interdisciplinary community effort.

4C will synthesise direct observations for atmospheric, oceanic and land carbon cycle and closely related variables (such as oxygen and carbon isotopes, plant solar-induced fluorescence (SIF), atmospheric carbonyl sulphide (COS) as well as land water storage and exchanges, etc.), and develop observation-based products for ocean and land carbon cycles. Careful consideration will be given to quantify the uncertainties in observations and methods. The observation-based products will provide unique metrics and constraints to assess the current land and ocean carbon sinks (size, variability, and underlying processes), quantify their evolution over the historical period and their sensitivity to environmental changes (mainly changes in atmospheric CO_2 and climate), and evaluate their representations in models.

4C will work over multiple time-scales, making use of the rich observational base of the recent past to improve understanding of underlying processes. We will provide and use observation-based products: (1) at the interannual time-scale (satellite xCO_2, SIF, COS, land-water data reconstructions) to constrain the processes that are responsible for interannual variability (IAV) in land carbon fluxes (i.e. primary productivity, respiration, wildfire and other disturbance on land and associated processes), recognising that although land carbon models produce a large land contribution to the observed atmospheric CO_2 variability, they currently do this for very different reasons[23]; (2) at the decadal and semi-decadal time-scale (atmospheric O_2 budgets, neural network based ocean surface pCO_2 flux, ocean carbon stock) to constrain processes responsible for variability in the oceanic carbon sink, recognising that although these new data-products suggest that ocean carbon sink variability could be far larger than suggested by models[24], its causes are poorly understood, and finally (3) at the decadal to century time scale (^{13}C trends and ^{13}C budget) to provide an independent estimate of the mean and trend in carbon sinks, and thus complement findings of the Global Carbon Budget currently based on the CO_2 budget alone[2]. We expect that improving understanding and model representation on seasonal to multi-decadal time-scales, where we have observations, will help improve key processes in models, reduce the B_{IM} over the historical period, and reduce uncertainties in model projections. This includes improvements in the representation of nutrient limitation, water stress, wildfires, permafrost on land, and mesoscale, biological export, and internal and externally-forced variability in the ocean (see Section 1.4). New and improved observation-based products will be used along with existing observations to evaluate carbon cycle models, provide our best estimate of the global carbon budget, and implement model improvements as diagnosed during the model evaluation. This procedure will be conducted every year of the 4C project to ensure continuous improvement in process understanding and representations in Earth System Models (ESMs), also allowing more robust attribution of the observed changes in the contemporary carbon cycle, and increased confidence in model predictions and projections.

1.1.3 Overall objective 2: Towards a near-term prediction of the climate and carbon cycle

Overall objective 2 of 4C is to develop new tools and methods to predict, for the first time, the evolution of global carbon cycle variability over the coming decade, including atmospheric CO_2, land and ocean carbon sinks, and climate response to track the overall progress towards the goal of the Paris Agreement.

IPCC AR5 near-term climate predictions only focused on the climate response over the coming decades, assuming atmospheric CO_2 follows the Representative Concentration Pathways RCP4.5 scenario[25], which is not specifically relevant to the Paris Agreement LTTG, and ignoring the uncertainty arising from the carbon cycle response to emissions. The slowdown in global warming that emerged over the first decade of the 21st century took the research community by surprise. Climate scientists were not able to account for what was happening[26], which prompted a wave of climate scepticism among the public. A similar "climate surprise" could occur again in the near future, if for example, atmospheric CO_2 concentration was changing at a rate that would seem inconsistent with reported trend in global emissions. The research community needs to be able to understand the processes at play and to clearly communicate these, in order to enable appropriate policy responses. Even on a year-to-year time scale, the reporting of changes in atmospheric CO_2 growth rate, primarily caused by natural fluctuations of land and ocean carbon sinks[27,28], is often misinterpreted as reporting of emissions growth rates[29]. Such misunderstandings could be addressed with the development and deployment of a near-term carbon cycle prediction system.

We will first assess the predictability of the carbon cycle system, both over land and in the ocean, via ESM control experiments and decadal hindcasts over the last 60 years. We will then explore predictions of the carbon system in the near-future, assuming anthropogenic emissions follow the United Nations Framework Convention on Climate Change (UNFCCC) Nationally Determined Contributions (NDCs) and quantify the direct impact of emission reductions on CO_2 concentrations, accounting for the natural variability of the climate system and the carbon sinks. This new knowledge will be a major step to facilitate the verification of near-term emission trends, and in particular the timing of any emissions peak, providing policy-relevant analysis for the UNFCCC global stocktakes.

This overall objective 2 will be tightly connected to the overall objective 1 by making use of the new observation-based products to reduce uncertainties in near-term predictions. Our current partial understanding of the global carbon cycle, illustrated by the carbon budget imbalance (B_{IM}) severely limits our capability to detect any near-term changes in atmospheric CO_2, and therefore to correctly attribute such changes to emission mitigation efforts or to internal natural variability of the climate-carbon system (Figure 2)[29]. Assuming that B_{IM} annual errors are 0.7 $GtCyr^{-1}$ on average (with possible multi-year excursions of 1-2 $GtCyr^{-1}$) in the near future, it would take 10 to 20 years to detect a 1% change in the increase of CO_2 emissions at the 68% confidence level (e.g. from the 1% per year increase of the past few years to a 0% per year, i.e. emissions stabilization). To reduce this detection time and thus provide meaningful near-term predictions of atmospheric CO_2 and the carbon cycle, we will use the new observational constraints in two ways: first to assist in the choice of the initial conditions that best approximate observations of the land and ocean carbon reservoirs; and second to provide stronger constraints, and potentially apply bias corrections, on the temporal evolution of the simulated land and ocean carbon sinks. While overall objective 1 of 4C will help reducing the B_{IM} over the historical record, this will also benefit overall objective 2, which aims to (a) reduce the time window for the detection of trends in CO_2 emissions in the near term, and (b) build confidence in a decadal prediction system of the coupled climate and carbon cycle system.

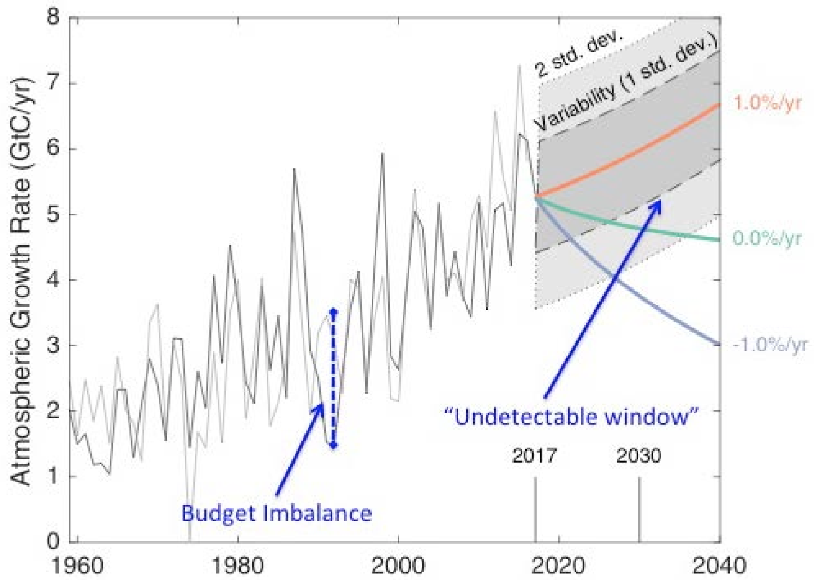


Figure 2. Uncertainty in the near-term carbon budget. Atmospheric CO_2 growth rate (black) vs. simulated growth rate from modelled carbon sinks (grey), the difference being our current budget imbalance (B_{IM}). The grey zones (1 and 2 σ) in the future illustrate the lack of predictability, estimated by the standard deviation of B_{IM} in the past. Without a better understanding of climate-carbon interactions, it would take about 10 to 20 years to detect a 1%/year change in emissions growth rate (orange vs. green line) (adapted from Peters et al., 2017).

1.1.4 Overall objective 3: Reducing uncertainties in climate projections over the 21st century

Overall objective 3 of 4C is to improve our understanding of climate-carbon feedbacks and provide a robust quantification of their evolution over the 21st century, using new constraints from historical observations to inform the analysis of ESM projections.

The IPCC AR5 provided the first consensus assessment of TCRE and carbon budget for the 2°C LTTG, but with such a large uncertainty as to limit its utility in policy decisions. IPCC assessed that TCRE is *likely* in the range of 0.8°C to 2.5°C per 1000 GtC (vertical blue bar on Figure 3), and that limiting the warming with a 66% probability to less than 2°C will require cumulative CO_2 emissions to stay below about 790 GtC (red arrow Figure 3). However, the individual model estimates ranged between about 650 and 1350 GtC, due to large uncertainties in climate and carbon feedbacks (horizontal red bar Figure 3), mainly because the IPCC estimate was based on a small set of ESMs, with a carbon cycle largely unconstrained by observations[10].

As important, the IPCC estimates were based on the non-mitigation RCP8.5 scenario, not designed to inform on the likelihood to remain below 2°C, with the carbon budget being diagnosed by the time at which the scenario exceeds 2°C and for the specific CO_2 and non-CO_2 forcing of the RCP8.5 scenario[30]. For ambitious mitigation scenarios, with potentially significant overshoot followed by negative emissions, even the sign of the combined land and ocean carbon feedback is largely unknown[31]. Reduced uncertainty in the TCRE is therefore needed to provide greater clarity on CO_2 emissions pathways and carbon budgets consistent with the goals of the Paris Agreement[32].

4C will make use of existing CMIP6 (Coupled Model Intercomparison Project Phase 6) and new post-CMIP6 ESM configurations (in this proposal we will call these enhanced models "CMIP6+ ESMs"), combined with existing and novel emergent constraints[33-35] to reduce the uncertainty in carbon and climate projections, TCRE and remaining cumulative emissions. 4C will develop novel emergent constraints such as terrestrial water storage, evapotranspiration, SIF and COS for terrestrial carbon uptake; seasonal air-sea CO_2 flux, ocean interior carbon content, and tracer (CFCs, SF_6) measurements for the ocean carbon uptake and biological carbon export, and new emergent constraints for processes recently included in ESMs (fires, permafrost).

Article 4 of the Paris Agreement also aims "*to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century*." However, achieving this "balance" will depend on carbon cycle feedbacks: for instance, uncontrolled CO_2 losses from permafrost will require stronger emissions reductions to reach balance in CO_2 emissions. Global emissions balance will also depend on the contribution of non-CO_2 climate drivers such as methane, nitrous oxide or potentially aerosols[36].

A key limitation of the TCRE and budget approach is their exclusive focus on CO_2. 4C will develop new physically-based approaches to relating CO_2 emissions and non-CO_2 climate drivers, developing the concept of "*CO_2-forcing-equivalent emissions*"[37]. This allows non-CO_2 forcing agents to be incorporated into CO_2-based emission budgets in a physically consistent way, accommodating lifetime differences that are obscured by conventional "CO_2-equivalent emissions" metrics.

4C will also develop innovative new adaptive emission scenarios, where the emission mitigation effort is revised every 5 years in light of the realised radiative forcing and warming simulated by the ESM models during the course of the 21st century, in such a way that emissions approach zero (net carbon balance) when global warming approaches the given climate target (1.5 or 2°C). A large rate of warming (i.e. a large TCRE) would require implementing deeper emission reductions; conversely a moderate rate of warming would allow for a slower rate of emission cuts. This approach is consistent with the proposed 5-year cycle of "stocktakes of ambition" introduced by the Paris Agreement. Combined with our reassessment of carbon feedbacks and TCRE, and accounting for the contribution of non-CO_2 forcing, it will allow us to provide, for the first time, our best estimate of carbon emissions fully consistent with the Paris agreement ambition to limit climate change below 1.5°C or 2°C under a periodic stocktake regime. One of the key outputs of 4C is to provide the "best available science" to support the Paris Agreement. In particular, we will address the danger that Parties might relax their ambitions prematurely, should either global emissions appear to fall unexpectedly fast, or atmospheric concentrations rise unexpectedly slowly, over a 5-year stocktake cycle due to uncertainties and variability in the global carbon cycle.

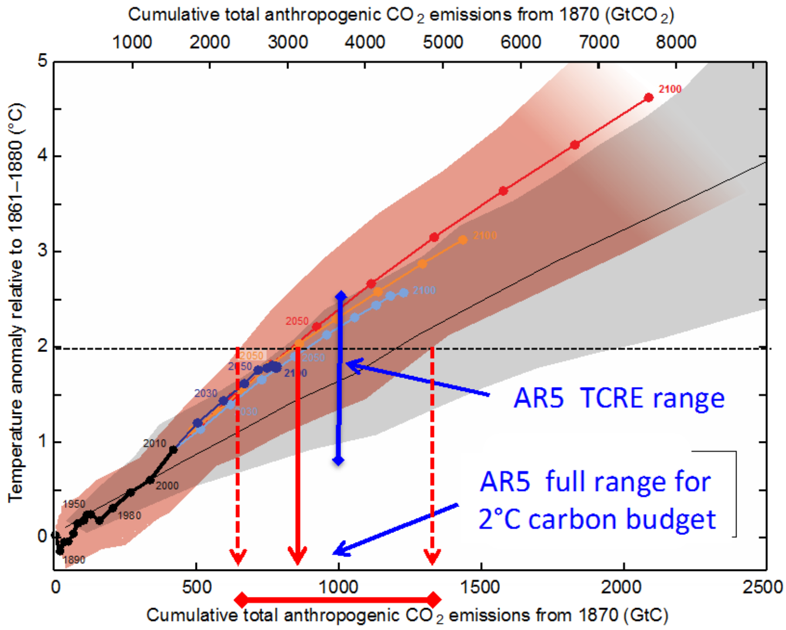


Figure 3. Uncertainty in the long-term carbon budget. Global surface temperature change as a function of cumulative CO_2 emissions for 1%/year CO_2 increase (grey) and RCP scenarios (colours). The vertical blue bar represents the AR5 likely range for TCRE; the red arrow shows the AR5 estimate of the cumulative CO_2 emissions for a 66% chance to remain below 2°C, and the horizontal red bar represent the full AR5 ESMs range for this estimate (adapted from IPCC AR5 WG1 SPM).

1.1.5 Objective 4: Knowledge transfer

4C will ensure the usability of the knowledge generated by scientific research and engage in bilateral interactions among scientists and policymakers, while also fostering the understanding of the findings for the broad society.

Innovative findings come hand-in-hand with challenges in communication and knowledge transfer. Solving knowledge gaps in carbon cycle interactions requires scientific results – from objectives 1, 2 and 3 - and their correct interpretation. However, once a concept is grasped it needs to be further elaborated to become usable information. When dealing with technical content the obstacles between receiving the information and using it are particularly high. Knowledge transfer implies the synthesis of 4C scientific findings to foster understanding of the concepts and, importantly, enhance the usability of the information conveyed. Explaining a finding can be unidirectional but transferring knowledge requires both parties to understand each other's perspectives. To achieve this, two-way interaction between scientists and policy and decision makers is necessary. The 4C project will go beyond explaining project findings by integrating the perspectives and needs of policy and decision makers into the scientific process. Findings will be shaped in such a way as to feed smoothly into decision-making processes (e.g. the annual UNFCCC Conferences of Parties). In addition, 4C will assist international scientific assessments (e.g. IPCC, IPBES GCP, WMO State of the Climate, UNEP Emissions Gap Report, etc.). The project is designed to provide timely support to IPCC assessments and to ease the exploitation of the results by the scientific community using solutions detailed below.

This knowledge transfer is transversal to the three above-mentioned overall objectives. 4C will make use of different types of communication, dissemination and engagement activities to facilitate knowledge transfer and bring benefits to the scientific community, policy and decision makers, and the broader society. Different approaches will be tailored for each of the targeted audiences.

The newly developed ScienceBrief platform (http://sciencebrief.org) uses the power of ICT to help keep up with a rapidly growing scientific literature. ScienceBrief will facilitate the exchange of research findings among the research community and between researchers and users of science. Building on the ScienceBrief Carbon Cycle pilot, 4C will improve user experience of the platform and work to significantly enhance its reach. Initially, the platform will harvest the latest findings to contribute to IPCC AR6, which will also receive specific support by an ad-hoc discussion panel involving IPCC AR6 lead authors. Presenting results at conferences, workshops and other traditional channels (e.g. the annual conference of the European Geophysical Union) will also be an important mean to foster interactions within the scientific community.

Directly supporting decision makers, 4C aims to provide added value by translating the emerging scientific understanding into a format that can inform policy decisions. Organization and active participation in policy relevant events is the starting point of a bilateral conversation. On the one hand, the events will be designed to communicate key findings; on the other hand they will serve to receive inputs from policymakers in order to understand their needs - with particular attention given to the Paris Agreement goals, with a dedicated workshop in Brussels. These continuous exchanges will also feed into a Policy Brief towards the end of the project. Combining the relevant scientific findings with an overview of the state-of-the-art CO_2 emissions policies and pledges, an analysis of the potential ways forward will be conducted resulting in policy recommendations (at European and possibly National level). In addition, 4C will also provide updates at each phase of the project with user-oriented fact sheets, which will be produced according to the development stage of the research. The goal is to build the knowledge base of our project's users and build trust in the 4C results, impacting positively on the engagement. Additionally, to enhance outreach, key outcomes of the project will be published in form of Carbon Outlooks - in partnership with the annual Global Carbon Budget (every autumn for the duration of the project).

The visibility of the project is pivotal to reach all targeted stakeholders and society at large. 4C therefore includes a comprehensive communication plan (section 2.2). 4C will create outreach pieces adapted to the general audience (e.g. opinion editorials, interviews, videos, and info-graphics) building on considerable and demonstrated expertise within the 4C consortium that, together with social media actions, will help to raise awareness of the general public.

1.1.6 Overview and approach

To achieve these four objectives, we will employ:

- New observations to better constrain the contemporary carbon cycle and its variability on seasonal to multi-decadal timescales. These include combined CO_2 and ^{13}C atmospheric measurements, atmospheric and oceanic O_2 data, and satellite atmospheric CO_2 that together will enable the identification of underlying processes and drivers of variability.
- New and improved data-based products to evaluate 4C carbon cycle models and to guide and improve process representation so as to reduce the carbon budget imbalance. These include water fluxes and storage on the land, neural network-based upscaling of surface ocean pCO_2 measurements, ocean interior changes in carbon stocks, new atmospheric data of CO_2, O_2 and COS, satellite observations of SIF of land vegetation that together will provide new information on ocean carbon uptake and vertical export as well as land photosynthesis and related carbon sink. A full list of novel data used in 4C is given in Tables 1.1a and 1.1b.
- State-of-the-art ESMs and their individual components including post-AR5 and post-CMIP6 physical and biogeochemical processes that are of importance for climate and carbon feedbacks (CMIP6+ ESMs). For the land carbon cycle, we will include recent and on-going development of nutrient limitations to

photosynthesis and hence carbon sinks; wildfires, permafrost and peat carbon and the responses of these processes to climate change; and improved representation of land management. For the ocean carbon cycle, we will employ high-resolution (eddy-permitting) models to improve representation of mesoscale transport and simulation of the Southern Ocean CO_2 uptake and its variability; include recent and ongoing development in riverine and atmospheric input of nutrients; and advanced marine ecosystem models including upper trophic levels (e.g. macrozooplankton processes) & explicit bacteria, as well as variable stoichiometry.

- Novel ESM-based decadal predictions, using CO_2 concentration-driven and CO_2 emission-driven configurations.
- Novel ESM-based diagnoses of CO_2-forcing-equivalent emissions corresponding to full multi-gas and multi-forcing-agent emission pathways to provide a fully physically-based interpretation of both "peaking" and "balance" of aggregate emissions, accounting for uncertainties in both the properties of other forcing agents and in the carbon cycle used to diagnose CO_2-forcing-equivalent emissions.
- Novel emergent constraints and weighting methods to reduce uncertainty in future projections of TCRE, carbon cycle feedbacks and climate. These will integrate new observational datasets, including e.g. on land water or ocean CFCs and SF_6 measurements, which have shown potential to reduce systematic biases in current models.
- Novel adaptive scenarios to drive the 4C ESMs in their CMIP6+ configuration to provide best estimates of carbon budgets consistent with the Paris Agreement ambitions, accounting for the major Earth system feedbacks.
- Enhanced ESM Evaluation Tool (ESMValTool), building on previous EU projects (in particular EMBRACE and CRESCENDO), with a recommended set of diagnostics and metrics for evaluation of the carbon cycle and climate-carbon feedbacks and constraints on TCRE and future projections.
- First extensive use of the novel ScienceBrief ICT platform to synthesise results on climate-carbon interactions and keep them up to date, and efficiently inform IPCC and other international assessments in a background of rapidly growing scientific literature.

In summary, 4C will make a major advance in our understanding of the key processes regulating the interactions and feedbacks between the carbon cycle and the physical climate system, using observational constraints and improved process understanding to provide, for the first time, harmonized near-term predictions and long-term projections of the coupled climate-carbon system under ambitious mitigation scenarios. This will allow the 4C team to deliver policy-relevant and observationally-constrained carbon dioxide emission pathways consistent with the Paris Agreement ambitions. Via its objectives, 4C will support two central elements of the UNFCCC Paris Agreement: the 2023 and 5-year global stocktakes to track progress towards the long-term goal; and the mitigation effort to achieve a long-term goal of keeping the increase in global average temperature to well below 2°C.

1.2 Relation to the work programme

The **4C** project addresses the H2020-LC-CLA call: "**Building a low Carbon, Climate resilient future: Climate action in support of the Paris Agreement"**. With reference to the call text in bold, we detail how 4C addresses key objectives of the call.

"Actions in this call aim to produce solutions for the achievement of the Paris Agreement's mitigation and adaptation goals, and to further relevant scientific knowledge for the implementation of the Nationally Determined Contributions (NDCs) and in advance of key Paris Agreement-related milestones, such as the publication of national mid-century strategies (2020), the 6th IPCC assessment cycle (2018-2022) and the first global stocktake in 2023."

4C will provide improved knowledge of the likely outcome of NDC implementation for the first global stocktake in 2023 and lay the scientific foundations for improved analysis in the subsequent stocktakes. 4C will develop the capability to simulate the expected changes in atmospheric CO_2, carbon cycle and associated climate change over the coming decade, combining the effect of the implementation of the NDCs with the intrinsic natural interannual to decadal variability of the coupled climate and carbon cycle system. This will allow policymakers to better anticipate the evolution of the carbon cycle and climate, in advance of key Paris Agreement-related milestones.

"Specific efforts have to be paid to communicating research results to a broader audience, including the larger public"

4C participants have very extensive experience in science communication to policymakers and other stakeholders. A key example of this expertise is the growing success and reach of the annual updates of the Global Carbon Budget, led by 4C partners, with key messages referenced in high-level political discussions (e.g., UN Secretary General, UNFCCC), policy making (government documents or discussions), mainstream media (reported in most widely read print and online media), and increasingly social media. 4C will build on this expertise and experience, and aim to reach deeper into decision and policy making with targeted and novel activities. 4C includes a strong component on communication, with its WP4 entirely devoted to synthesis, dissemination, and policy dialogue. Each audience will have focussed activities: science summaries and other dissemination tools will aim to first improve the general understanding of carbon cycle science amongst decision and policymakers, and then build on this to communicate main findings in the context of other emerging science and policy discussions. Building on the science summaries additional products will be produced for mainstream and social media (e.g. opinion editorials, interviews, videos, info-graphics). A strong focus will be placed on communicating to scientific peers that feeds into the IPCC process and broader scientific discussions. Activities will build on the highly successful annual Global Carbon Budgets to ensure that 4C 1 to 10-year forecasts, and insights on climate-carbon interactions are effectively communicated. Science communication expert I. Jimenez (BSC) will be the lead and Research Director G. Peters (CICERO) the deputy lead of WP4, with contribution from most partners to ensure the science is optimally communicated.

4C will address the topic **"LC-CLA-08-2018: Addressing knowledge gaps in climate science, in support of IPCC reports"**.

As described in section 1.1, 4C has three overall scientific objectives, each addressing a critical knowledge gap we have identified in the IPCC 5th Assessment Report. The first objective is to significantly reduce the uncertainty in the historical carbon budget, combining existing and novel observations with state-of-the-art global carbon models, focusing on key land and ocean processes that can contribute to the budget imbalance on annual to decadal time-scales. The second objective is to develop novel ESMs-based decadal predictions driven by anthropogenic CO_2 emissions in order to forecast the near-term evolution of the atmospheric CO_2 and climate response in the context of the global stocktake. The third objective is to significantly reduce the uncertainty in carbon cycle feedbacks and climate projections, and in particular to provide a more robust estimate of TCRE for mitigation scenarios in the context of the Paris agreement. 4C will directly support the IPCC reports. We are aware that for AR6, the Working Group 1 cut-off dates for scientific papers to be assessed will be 30/12/2019 (paper submitted) and 30/09/2020 (paper accepted), and hence we have a strategy to deliver early results from 4C within that time-frame. In addition, the 4C 2nd and 3rd overall objectives are also relevant to the WG2 and WG3 reports, both having later cut-off dates.

Specific challenge: "Better understanding of the key processes controlling the climate-Earth system is fundamental in order to further improve climate projections, reduce uncertainty in climate sensitivity calculations"

4C's main objective is an improved understanding of the fate of anthropogenic CO_2 in the Earth System, better characterising the role of land and ocean in removing CO_2 from the atmosphere, and in particular the under-explored response to falling emissions in high mitigation scenarios. 4C will utilize a hierarchy of models to enable a comprehensive exploration of the interactions between the climate system and the global carbon cycle, over the historical period, in the near-term up to 2030 and over the full 21st century. 4C will make use of state-of-the-art ESMs, accounting for key biogeochemical processes not included at the time of AR5, assessed against comprehensive observations and new emergent constraints of the land and ocean carbon cycle and related variables in order to improve climate projections for given CO_2 emission scenarios and to significantly reduce the uncertainty on the estimates of the transient climate response to CO_2 emissions (TCRE), a quantity that **"provides added-value to decision and policymakers"**.

4C aims to address the first topic of this specific challenge: **"Improving the understanding of key climate processes for reducing uncertainty in climate projections and predictions". Actions should achieve better understanding of key processes, and associated feedbacks, affecting the climate-Earth system over time, in order to improve climate projections and predictions and constrain climate sensitivity estimates.**

4C will improve our understanding of the key biogeochemical processes (and associated physical drivers) responsible for carbon sinks and their response to climate change, making use of an unprecedented amount of global atmospheric, oceanic, and land carbon cycle observations to improve our understanding of the causes of trend and variability of the carbon cycle over the recent past, which is critical for improving our confidence in near-term prediction and for better constraining our long-term projections. In particular, following the previous H2020 projects on ESM developments (e.g. EMBRACE, CRESCENDO) and other national projects, 4C will assess and further refine the land nutrient cycle, permafrost, wildfire and land-use components of CMIP6+ ESMs used and improved in the project, aiming to better understand the key control of nutrients, disturbance and land management on land carbon sinks. 4C will also use advanced marine biogeochemical models, benefiting from the recent model developments of past projects. In particular, marine biogeochemical models will be embedded within higher resolution physical ocean models than in the previous generation of ESMs. The high resolution ocean models can simulate small scale eddies that are thought to be important for simulating the upwelling strength and its sensitivity to climate variability in the Southern Ocean, and may therefore also be critical to better resolve the decadal variability in the Southern Ocean carbon sink. The marine biogeochemical models will also employ refined ecosystem components (e.g., with explicit bacteria, upper trophic levels, and variable stoichiometry), and include improved products for nutrient and carbon atmospheric and riverine inputs.

"Action may cover processes such as biogeochemical cycles and their evolution under a changing climate, ocean dynamics and circulation, dynamic interactions between atmosphere, land, and ocean and ice"

4C will bring together 12 partners with a unique expertise on global biogeochemical cycles, oceanic physics, land-atmosphere interaction and Earth System modelling in the context of climate change. Five state-of-the-art ESMs in configuration similar to CMIP6, combined with their enhanced CMIP6+ versions where key new processes in land and ocean carbon models components will be assessed and further improved over the course of the project, providing a measure of the remaining uncertainties due to different process representations across the models.

1.3 Concept and methodology

1.3.1 Concept

The overall concept underpinning 4C is to use of a large set of existing observations (Table 1.1a) and develop new or update existing observation-based data products (Table 1.1b) to constrain the CMIP6+ ESMs (Table 1.2), a novel near-term initialisation and prediction technique, and original policy-relevant climate scenarios to provide a deeper understanding of the climate and carbon cycle interactions on the three critical time scales relevant to 4C:

- the historical period (1900-2020), as a unique test-bed of our capability to understand the key processes that control the changes in atmospheric CO_2, and in particular the importance and response of the land and ocean carbon reservoirs to interannual to multi-decadal climate variability;
- the near-term future of the carbon cycle, from next year to the coming decade, as the critical time window to inform on the integrated effectiveness of the sequential implementation of the Paris Agreement;
- the full 21st century, as the central time frame to ensure the success of the Paris Agreement in limiting climate change.

Recent EU projects (e.g. EMBRACE, CRESCENDO), along with nationally funded research, have led to substantial developments of the biogeochemical and biophysical components of European ESMs (e.g. Land: nitrogen and phosphorous cycle, permafrost; Ocean: high-resolution (eddy-permitting) model, organic remineralisation from bacterial and zooplankton processes, variable stoichiometry). However, many of these most recent developments have not been fully integrated into the standard CMIP6 ESMs configurations or comprehensively tested against a large range of carbon cycle and related observations. 4C will build on the CMIP6+ models that are being developed now and over the course of the project, to further assess the climate-carbon interactions over the historical period, improve our understanding of key processes controlling the carbon cycle and its sensitivity to environmental changes, and reduce uncertainties in decadal predictions to centennial projections. A full list of models and configuration is given in Table 1.2.

4C will perform simulations with three main European ESMs (MPI-ESM, IPSL-ESM, and EC-Earth ESM) for near-term predictions, with the addition of two ESMs originally developed in the US (NCAR-CESM2 and GFDL-ESM2M) for the long-term projections. 4C will also include Bern3D-LPX, a cost-efficient Earth System Model of Intermediate Complexity to explore novel adaptive scenarios. Offline simulations (land and ocean physical and biogeochemical models forced by observed climate forcing) will be performed in addition to support the analysis over the historical period. Table 1.3 summarises these project specific simulations, their main purpose along with the list of participating models.

Table 1.1a Available existing observations and observation-based data products used in 4C

Data	Constraint on	Record length	Spat. res.	Temp. res.	Usage in 4C	Ref
Air-sea CO_2 flux SOCAT and BGC Argo	Air-sea CO_2 flux	1982-present	1°x1°	monthly	WP1 evaluation WP2 bias correction, skill assessment, validation of initial conditions (IC) WP3 emergent constraints (EC) on ocean sink	38
GO-SHIP Ocean interior C, heat	Ocean C content	1994-present	1°x1°	Time slices	WP1 evaluation WP2 validation of IC WP3 EC on ocean sink	39
Ocean CFC-11, CFC-12 and SF_6	Ocean C content	1982-present	1°x1°	Time slices	WP1 evaluation WP2 validation of IC WP3 EC on ocean sink	40
Observations of terrestrial water storage (GRACE)	Water storage changes	2003-present	1°x1°	monthly	WP1 evaluation WP2 validation of IC WP3 EC on land sink	41
Statistical reconstruction of water storage	Water storage changes	1901-present	1°x1°	monthly	WP1 evaluation WP2 validation of IC WP3 EC on land sink	42
Synthesis dataset of evapotranspiration	ET	1989–2005	various	monthly	WP1 evaluation WP3 EC on land sink	43
Upscaling of ET and C fluxes (FLUXNET)	GPP, NBP, ET	1950-2014	0.5°	daily	WP1 evaluation WP2 bias correction, skill assessment, validation of IC WP3 EC on land sink	44
SIF (Solar induced fluorescence)	GPP	2001-2016	0.05°	4-day	WP1 evaluation WP3 EC on GPP	45
Atmospheric COS	GPP	2000-present	stations	monthly	WP1 evaluation WP3 EC on GPP	46
Vegetation Optical Depth (VOD)	Biomass	2010-2018	~0.5°	monthly	WP1 evaluation	
LAI (MODIS)	Leaf Area Index	2000-2018	0.5°	monthly	WP1 evaluation	
Burned area (GFED)	Fire	1998-present	0.25°	monthly	WP1 evaluation WP3 EC on fire	47
Satellite XCO_2	Atmospheric CO_2, C fluxes	2003-present	2°	monthly	WP1 evaluation WP3 EC on C sinks	48
Scripps, UEA Atm O_2	O_2 and APO budgets	1989-present	>10stations & ship line data	monthly	WP1 evaluation and carbon budget	49
NOAA, Scripps, CSIRO Atm ^{12}C, ^{13}C (CO_2)	^{12}C and ^{13}C carbon budgets	1958-present (^{12}C); 1977-present (^{13}C)	45 stations	Discrete samples	WP1 evaluation and carbon budget	50
- GLODAP ^{13}C(DIC) - Ice and firn 13C - Tree-ring ^{13}C - Leaf ^{13}C	^{13}C carbon budget	Preindustrial & modern 1000-2001 1900-2000 modern	1°x1° Global 76records 594sites	decadal decadal Samples decadal	WP1 evaluation and carbon budget	51 52 53 54

Table 1.1b New or updated observation-based data products generated by 4C

Data	WP/Task	Status	Size	Availability
Satellite XCO_2	WP1 T1.1.3	Existing product, updated to present	10Gb/yr	Publicly available
Neural network air-sea C fluxes	WP1 T1.2.1	Existing product, updated to present	<1Gb	Publicly available
Ocean interior C change	WP1 T1.2.2	New product	<1Gb	Publicly available
Terrestrial Water Storage	WP1 T1.2.3	Existing product, updated to present	<1Gb	Publicly available
Land-Flux EVAL dataset (ET)	WP1 T1.2.3	Existing product, updated to present	<1Gb	Publicly available
Machine learning Forest NBP	WP1 T1.2.4	New product	<1Gb	Publicly available

Table 1.2 Characteristics of 4C models, with list of CMIP6+ processes

Model	Atm. Res. (°)	Ocn. Res. (°)	Land BGC	Ocean BGC	Ref.
ESMs					
MPI-ESM1.2 LR	1.8x1.8	1.5x1.5	JSBACH3: C-N, fires, dynamic veg., land-use	HAMOCC: C, O2, P, Fe, Si; ^{13}C, 4 PFTs, interactive ocean sediments, organic particle aggregation, riverine fluxes of nutrients	[55]
EC-Earth	1x 1	1 x 1	LPJ-Guess: improved wildfires, permafrost and global wetland CH_4, N_2O emissions	PISCES: C, O_2, P, Fe, Si, ^{13}C; 4 PFTs	[56]
IPSL-ESM	2.5x 1.5	1x 1	ORCHIDEE: C-N-P, dynamic veg., land-use, permafrost, peatlands, ozone damage, diffuse/direct light	C, O_2, P, Fe, Si, ^{13}C; explicit bacteria, 5 PFTs, internal quotas for N,P,Fe and Si of phytoplankton	[57]
NCAR CESM2	0.9x1.15	0.9x1.15	CLM5: C, ^{13}C, N, peat, crop, wood harvest	POP2/Marble: C, ^{13}C, N, P, Si, Fe, O_2	[58]
GFDL-ESM2M	2x2.5	0.3-1x1	LM3.0: C, N, dynamic veg., land-use, wood harvest	TOPAZv2: C, O_2, P, Fe, Si; 3 PFTs	[59] [60]
Earth System Model of Intermediate Complexity					
BERN3D-LPX	~10x5	~10x5	LPX-Bern: C, N, CH_4, N_2O, fires, wetland, permafrost, land-use	Bern3D: C, ^{13}C, ^{14}C, P, Si, Fe, O_2, etc., interactive ocean sediments	[61] [62]
Carbon cycle models (not described above)					
JULES	0.5x0.5 to 4x5	n.a.	JULES: C, N, fires, permafrost, land-use, ozone damage, diffuse/direct light	n.a.	[63,21]
NEMOv3.6-PlankTOM10	n.a.	2x0.3-1.5 and 0.25x 0.25	n.a.	PlankTOM10: C, ^{13}C, O_2, P, N, Fe, Si; 10 PFTs explicit bacteria and macrozooplankton	[64]

Table 1.3 List of 4C specific model simulations

Description	Simulation Period*	WP and Task	Simulation type and length	Models	Purpose
Forced historical run land carbon	1900-2020 (+1700-1899 ramp-up)	WP1 T1.3	Offline C models 120+ year long	JULES, ORCHIDEE LPX-Bern , JSBACH LPJ-GUESS	Understanding processes causing land carbon sinks; model evaluation
Forced historical run ocean carbon	1900-2020 (+1700-1899 ramp-up)	WP1 T1.3	Offline C models 120+ year long	NEMO-PlankTOM10, POP2, HAMOCC, NEMO-PISCES	Understanding processes causing ocean carbon sinks; model evaluation
Forced historical run ocean carbon high resolution	1989-2020	WP1 T1.3	Offline C models 30+ years long	NEMO-PlankTOM10	Quantifying the effect of small-scale processes on ocean carbon variability
Historical coupled simulation	1850-2014	WP1 T1.3	Online ESMs Emission-driven 165 year long	IPSL-ESM, EC-Earth, MPI-ESM, GFDL-ESM2M, NCAR-CESM2-C13	Evaluation of global carbon cycle; provision of starting point for decadal predictions; provision of emergent constraints,
Factorial experiments individual forcings	1900-2020	WP1 T1.3	Offline C models 120 year long	Same as models for forced historical runs	Attribution of carbon cycle changes to drivers
Perfect model decadal predictions	From control	WP2 T2.1	Online ESM 15 start dates x 15 members 10 year long	IPSL-ESM, EC-Earth, MPI-ESM	Assess potential predictability of climate-carbon system
Data-assimilated reconstruction	1958-present	WP2 T2.2	Online ESM 3 realizations x 60+ year long	Same as above	Provide initial conditions for hindcast and future predictions
Retrospective decadal predictions (Conc. driven)	1981-present	WP2 T2.3	Online ESM 30+ start dates x 15 members 40 year long	Same as above	Assess predictability against observations Bias correction estimate
Retrospective decadal predictions (Emis. driven)	1981-present	WP2 T2.3	Online ESM 30+ start dates x 15 members 40 year long	Same as above	As above + assess predictability of atmosph. CO_2 against observations
Future decadal predictions (NDCs)	present-2030	WP2 T2.4	Online ESM Emission driven 3 start dates x 15 members 10 year long	Same as above	Prediction of next decade (including next year) of atmospheric CO_2, carbon sinks, and climate
Future decadal predictions (baseline scenarios)	present-2030	WP2 T2.4	Online ESM Emission driven 3 start dates x 15 members 10 year long	Same as above	Baseline to allow attribution of future atmospheric CO_2 to NDCs vs natural variability.

Adaptive scenarios projections	2015-2100	WP3 T3.4	Online ESM Emission driven 3 scenarios 86 year long	IPSL-ESM, EC-Earth, MPI-ESM, GFDL-ESM2M, NCAR-CESM2-C13, Bern3D-ESM	Assessment of TCRE, remaining carbon budget and climate response

* End year of simulation period will be extended every year, lagging actual calendar year by one year, for simulations that are repeated annually in the project (Forced historical runs and Future decadal NDCs).

1.3.2 Methodology

4C will be divided into three science work packages (WP1-3), a synthesis, dissemination and policy dialogue work package (WP4), a management work package (WP5) and an ethics work package (WP6) as described below (Figure 4). The 4C science work packages (WP1-3) are aligned with the three overall objectives, each one closely connected to one time horizon: historical record, near-term future and long-term future, and they are constantly complemented by the transversal efforts of WP4 aligned with objective 4 ensuring knowledge transfer and enhancing the project impact.

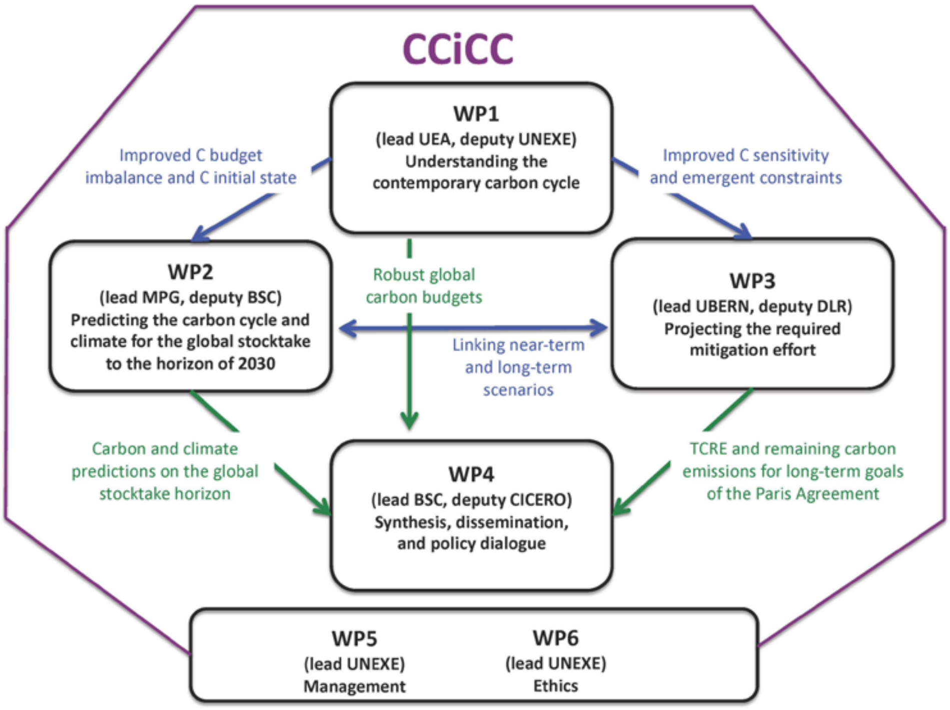


Figure 4. 4C Work Package structure and inter-connections between WPs. Blue arrows represent transfer of scientific data; green arrows represent transfer of scientific knowledge.

WP1 Understanding the contemporary carbon cycle

The objective of WP1 is to make an advance in our understanding of the carbon cycle over the historical period, as an essential prerequisite of reliable near-term predictions and long-term projections. This will be achieved by developing and making use of novel observations and data products to constrain the land and ocean carbon fluxes and their drivers, combined with forced land and ocean carbon cycle model simulations over the historical period (1900-2020), and fully coupled ESM simulations over the last 30 years to improve our understanding of underlying processes, particularly focusing on the response of carbon fluxes to increase in atmospheric CO_2, seasonal to decadal climate variability, and climatic extremes.

WP1 will be divided in 5 tasks: T1.1 providing new observational constraints, T1.2 providing improved data-based products, T1.3 providing historical model simulations to support the model evaluation against these observations and improvement of key process representations in T1.4 and the attribution of key drivers controlling the evolution and variability of the carbon sinks in T1.5.

WP2 Predicting the carbon cycle and climate for the global stocktake to the horizon of 2030

The objective of WP2 is to build the capability to perform decadal predictions of climate and the carbon cycle where CO_2 emissions (instead of concentrations) are being prescribed. This will be achieved along with an improved understanding of decadal variability of the climate-carbon cycle system, accounting for forced response and natural variability. We will use 3 European ESMs to develop and continually improve initialization techniques via validation against new observational products from WP1. The best-performing initialization technique will be used to perform future near-term predictions assuming anthropogenic emissions follow the UNFCCC NDCs ambitions and, as a baseline scenario, the RCP4.5. This will allow anticipating and explaining the near-term evolution (up to 2030) of atmospheric CO_2 increase and climate response, in time for the first global stocktake in 2023.

WP2 will be divided in 4 successive tasks. T2.1 will explore the mechanisms driving decadal predictability of the global carbon cycle by performing idealized process-oriented predictions. T2.2 will reconstruct the recent past (1958-present) to provide initial conditions for the retrospective predictions. These will be used in T2.3 to assess the predictability of the 3 ESMs over the last 40 years (1981-present). Finally, T2.4 will provide unique emission-driven predictions of the near-future (2020-2030) evolution of atmospheric CO_2, carbon cycle and climate when emissions follow either the UNFCCC NDCs or a baseline scenario, also including annually-repeated predictions of the next year's atmospheric CO_2 and carbon sinks.

WP3 Projecting the required mitigation effort over the 21st century

The objective of WP3 is to make use of existing and new observation datasets, developed in WP1, to better constrain long-term projections of the climate-carbon cycle system in the context of climate targets and remaining carbon emissions compatible with the ambitions of the Paris Agreement. Using the available CMIP6 simulations, T3.1 will develop emergent constraints on the carbon cycle to obtain observation-based improved understanding of the carbon cycle dynamics and biogeochemical feedbacks. In order to ensure that the emergent constraints are robust, these will be based on sound physical and mathematical principles, and tested 'out of sample' against models that were not used to derive the emergent constraint, using the approach outlined in a recent paper (Eyring et al., 2019, *Nature Climate Change*).T3.2 will reassess the transient climate response to cumulative CO_2 emissions (TCRE) in light of these new emergent constraints, also accounting for the warming induced by non-CO_2 emissions. T3.3 will combine emergent constraints and models' skills to reproduce the historical record, as provided by WP1, to provide original weighting of multi-model and large ensemble climate and carbon cycle projections. T3.4 will use our CMIP6+ ESMs to explore original adaptive scenarios, starting from the same NDC compliant scenario from WP2 for the first decade (2020-2030), followed by a "adaptive mechanism" where simulated climate change is diagnosed every 5 years and used to revise the emissions reduction needed to keep global warming below 1.5°C or 2°C. Emergent constraints developed in 4C will be used to further refine the estimates of remaining carbon budgets in these adaptive scenarios.

WP4 Synthesis, dissemination, and policy dialogue

The objective of WP4 is to assess and synthesise 4C scientific findings to foster a broader understanding of climate-carbon interactions to support international assessments, decision and policymakers, and the general public. We will facilitate knowledge transfer concerning our improved understanding of the human perturbation of contemporary carbon cycle; our understanding of the near-term evolution of the carbon cycle and how it would respond to near-term emission mitigation; and our understanding of the Earth System, accounting for climate and carbon cycle feedbacks in the context of the long-term ambitions of the Paris Agreement. WP4 will be divided in 4 tasks, T4.1 will focus on the knowledge transfer to support major international scientific assessments, T4.2 will provide added-value to decision and policymakers, while T4.3 will focus on the general public, and T4.4 will manage the project communication and dissemination in close collaboration with WP5.

WP5 Management

The management includes provision for the overall project management, interfacing with the Commission and third parties, reporting to the Commission, ensuring the project's objectives are met, the deliverables achieved, and managing project risks.

WP6 Ethics

This work package will address relevant ethics considerations principally concerning data protection issues.

1.4 Ambition

The ambitions of 4C builds on its four objectives: i) improved understanding of processes controlling the carbon sinks via an unprecedented assessment of the models against a large set of existing and new observations and the use of recent biophysical and biogeochemical developments integrated in post CMIP6 models (CMIP6+ ESMs); ii) novel annual to decadal prediction of the state of the carbon cycle and climate system; iii) reduction of uncertainty on long-term projections of climate and carbon cycle; iv) efficient dissemination of relevant results to a broad range of audiences from policymakers to the larger public.

1.4.1 Better quantitative understanding of processes controlling the global carbon cycle

By the end of the project, we have the ambition to improve our modelling of the processes regulating the land and ocean carbon sinks such that the combined carbon budget imbalance is reduced by a factor of two (mean absolute deviation of the B_{IM} decreasing from 0.7 $GtCyr^{-1}$ to 0.35 $GtCyr^{-1}$).

A measure of the current limitations in our understanding is provided by the amplitude of the carbon budget imbalance (B_{IM}), illustrated in Figure 1. 4C has the ambition to significantly improve our understanding of the global carbon cycle over the historical period, and in particular the last 60 years. This will be achieved mainly through improved process-based constraints on interannual variability, particularly on land; and on semi-decadal to decadal variability of the ocean.

To improve our current understanding, 4C will first collect and use an unprecedented series of global observational constraints to attribute the part of the B_{IM} caused by limitations in estimates of the land and/or ocean sink. This will include coherent times series of atmospheric CO_2, oxygen and carbon isotopes and COS, most recent satellite-derived observation (xCO_2 and SIF), as well as new development in observation-based products of air-sea CO_2 flux, ocean interior carbon stocks, and transient tracers (CFCs, SF_6), and land water, carbon and nutrients fluxes and stocks. This observation framework will provide unique observational constraints on the global carbon cycle and fill the gap between observations and ESMs, allowing us to comprehensively assess the land and ocean carbon cycle models over the recent past.

4C will focus particularly on the following processes:

a) Nitrogen and Phosphorous control on the strength of the carbon sink on land. Nutrient limitation affects the spatial distribution of land carbon uptake and its trend, limiting CO_2 fertilisation in heavily nutrient limited tropical and boreal and arctic high-latitude ecosystems, and increasing land carbon uptake in areas of high anthropogenic air pollution via nutrients atmospheric deposition[65]. However large uncertainties still exist in future projections of the magnitude and spatial extent of land nutrient limitation and their effect on long-term land CO_2 fertilisation and response to climate change[66]. Furthermore, nutrient limitation could also dampen responses to climatic variability, therefore reducing IAV in models. The participating state-of-the-art CMIP6+ land carbon models with improved representation of nutrient dynamics will be rigorously evaluated against C and N fluxes and pools datasets to corroborate their ability to simulate the carbon cycle dynamics at seasonal to decadal timescales. New constraints on GPP spatial variability from soil water storage, SIF and COS will also guide the insights on nutrient control. The specific role of nitrogen on land carbon sinks will be further assessed via attribution studies of the impact of anthropogenic N deposition of land (see item j below) and compared to observational constraints on the N sensitivity of land carbon storage derived from manipulation studies as a measure of N limitation[67,68]. Jointly, these analyses will provide more confidence in the potential nutrient limitation on carbon sinks in the future.

b) Land water control on land carbon sink: New evidence has revealed a strong global-scale control of land water variability on the IAV of the land carbon sink and the atmospheric CO_2 growth rate[69,70], although this response appears muted in most ESMs[34]. Observational constraints based on satellite measurements of terrestrial water storage[41], observations-based reconstructions of water storage for the 20th century[42], and new evapotranspiration datasets[71] will be used to further assess the temporal variability of simulated soil water content and its control on plant transpiration and photosynthesis and hence land carbon sinks. These analyses will provide improved understanding on land carbon dynamics on interannual time-scales (El Niño, droughts), with the potential to significantly reduce the B_{IM} on ENSO time-scales.

c) CO_2 emissions from permafrost, peatlands and their evolution in the 21st century. Permafrost carbon has been identified as potentially the largest land carbon pool vulnerable to climate change[72]. However, large uncertainties remain in the quantification of the potential carbon loss over the 21st century[73,74], with significant implications for the quantification of TCRE and the remaining carbon budget for climate target. Any carbon release from permafrost would imply a reduction in the remaining anthropogenic emissions. In 4C, we will evaluate state-of-the-art CMIP6+ land carbon models with improved representation of permafrost against observations of permafrost spatial extension and permafrost soil carbon content. Interaction with high-latitude warming, soil nitrogen mineralization and vegetation dynamic will also be investigated[75].

d) CO_2 emissions from wildfires and their interannual variability. CO_2 emissions from fires play an important role on atmospheric CO_2 interannual variability, with large emissions from tropical fires during El Niño years[76], potentially explaining some of the carbon imbalance (B_{IM}) over the historical period. On longer time-scales, climate change (e.g. droughts) is expected to alter fire regimes of most ecosystems, inducing climate-fires feedbacks[77,78], with potentially drought-related increase in fires counteracting REDD+ measures to reduce deforestation[79]. New developments in ecosystem fire modelling[80,81] will be assessed over the historical period, in synergy with the FireMIP international initiative[82]. These analyses will provide improved understanding of fire dynamics and sensitivity to droughts, with the potential to also significantly reduce the B_{IM} on ENSO time-scales.

e) Mesoscale physical ocean circulation control on semi-decadal variability of the ocean carbon sink. New analysis of carbon observations in the ocean surface[24] and interior[83] suggest that ocean carbon cycle models underestimate the variability in ocean CO_2 fluxes, especially in the Southern Ocean. This is most likely due to their poor representation of small-scale processes, particularly those associated with mesoscale eddy transport at scales of ~10-100 km, which is below current model resolution (~100-200 km in most global ocean carbon models[2]). Eddy transports are significant contributors to the meridional exchange of mass, heat, carbon and nutrients, for example across the Southern Ocean, and to the vertical exchange of momentum[84]. Eddy processes are parameterised in ocean models, but this parameterisation could dampen the multi-year dynamics which is associated with eddy transport[85]. An assessment of the size and cause of oceanic CO_2 variability will be done by first gaining a better quantitative understanding of the variability in both air-sea CO_2 fluxes at the regional level and the variability in carbon in the ocean interior over three decades, based on data synthesis and novel methodologies. The methodologies will further inform about the source of variability, i.e. natural vs anthropogenic. Then model simulations with eddy-permitting resolution will be used to explore the importance of ocean meso-scale processes, not currently explicitly included in ESM, on ocean CO_2 flux variability. Both the direct impact of ocean circulation on carbon in the ocean interior, and the indirect impact mediated by nutrients and ecosystem productivity, will be examined. The oceanic analysis will be done both globally and at the regional level, enabling the identification of specific circulation processes, such as eddy responses in the Southern Ocean, and coastal and equatorial upwelling in the tropics.

f) Biological carbon export control on the ocean carbon sink. The export of organic carbon from the ocean surface to the intermediate and deep ocean generates a flux of carbon in the ocean that is five times as large as the ocean carbon sink. Changes in the intensity of this 'biological pump' would almost directly translate into changes in the intensity of the ocean carbon sink on annual to century time-scales. Model simulations project reductions in carbon export of 5-10% this century driven by, among other processes, reductions in marine primary production[86], in part constrained by seasonal and interannual variability using the emergent constraint approach[87]. However current models only used simple representations of marine ecosystems, and did not account for more detailed ecosystem processes that have been shown to respond to temperature and changing oceanic conditions (stratification and nutrient availability). Here we will test the importance of key ecosystem processes on carbon export, including from organic remineralisation by bacteria and zooplankton[64] over the past decades, and from variable stoichiometry on the export of carbon. In 4C, we will assess how these processes improve the representation of carbon fluxes in the ocean making use of existing and new data, including Atmospheric Potential Oxygen (APO).

g) Internally and externally - induced variability. Modelled land and ocean CO_2 sinks vary in response to externally (anthropogenic and natural) forced variability and due to the internal (chaotic) variability of the Earth system. External forcings include, for example, changes in greenhouse gases, aerosols, explosive volcanic eruptions and solar variations, while typical expressions of internal variability are climatic modes such as ENSO or the North Atlantic Oscillation with associated carbon cycle responses[88,89], or variations on smaller scales unrelated to climate modes. There is evidence from fully coupled models that internal variability in the ocean carbon cycle could be larger than previously thought, leading to a potentially missed source of variabilityna. In addition, controls of the IAV of the land carbon sink also appear underestimated[34]. In ocean-only and land-only models as used in hindcast simulations, the CO_2 sinks vary in response to imposed atmospheric forcing conditions (mainly temperature and rainfall variability on land, wind and buoyancy in the ocean). Unfortunately, there are large differences in observations and reanalysis products used to force models[90,91] and these uncertainties affect CO_2 sink estimates in these models. An assessment of the contribution of potential error in forcing products and missed internal variability will be done to identify sources of errors in the current methodologies for estimating CO_2 sinks in the past.

To assist in the understanding of how key processes control the global carbon cycle, we will further provide quantitative analysis of the land and ocean sink variability and trends, first by applying the approach based on the Global Carbon Budget using associated variables and second by applying methods of detection and attribution used in climate research to carbon cycle variables. This includes the specific analysis of:

h) Ocean and land responses to climatic drivers over semi-decadal time-scales using atmospheric O_2 observations. 4C will provide a further constraint on the oceanic and land CO_2 sink variability using observations of APO and building a global annual budget for APO and atmospheric O_2 since 1991. APO combines atmospheric O_2 and CO_2 in a way that is invariant to biospheric exchanges, and therefore enables the isolation of oceanic fluxes alone[49]. On land, O_2 and CO_2 are taken up and released by photosynthesis and respiration in equal (and known) ratios. Similarly, fossil fuel combustion has known ratios for CO_2 and O_2. In the ocean, O_2 and CO_2 are affected by the same processes of physical circulation and biological productivity, but in different proportions. Furthermore, O_2 is not influenced by the increase in anthropogenic CO_2 in the atmosphere, and therefore its signature reflects strongly the Earth system variability. Therefore, a global APO budget will provide independent constraint on oceanic responses to variability in climatic drivers, that will be used to identify the origin of the carbon budget imbalance, B_{IM}, while a global budget for O_2 will provide constraints on the sum of fluxes from the ocean and land as reproduced by models, and therefore provide independent information on the origin (land and/or ocean) of the B_{IM} identified through the Global Carbon Budget. The trends and changes in seasonal amplitude will also be examined to infer underlying processes. This analysis will be done both on observations directly, with particular attention given to the assessment of uncertainties (e.g. heat flux, rectifier effect), and integrated with models to verify how models reproduce variability and trends in APO and O_2. This activity should help in constraining processes driving the variability of the land and ocean carbon sinks, hence helping to reduce the magnitude of the B_{IM}.

i) Ocean and land responses to increasing CO_2 over decades-to-century using atmospheric ^{13}C. 4C will provide further constraint on the land and ocean trends using atmospheric ^{13}C signature. This signal is decreasing due to the addition of ^{13}C-depleted anthropogenic carbon from fossil fuel burning and land use. $^{13}CO_2$ is exchanged between the atmosphere, ocean, and the land biosphere through air-to-sea and sea-to-air gas exchange and by photosynthesis and respiration on land. Each of these transfer fluxes is characterized by an isotopic fractionation, influenced by climate processes. Analyses of ^{13}C observations therefore provide independent and integrated constraints on the two-way carbon exchange fluxes (magnitude, trend and variability) and the redistribution of anthropogenic carbon in the Earth system. This will provide an independent estimate of the land and ocean carbon sinks and the underlying two-way carbon exchange fluxes and isotopic disequilibria, and also provide isotopic constrains on future carbon sink projections. As for APO and O_2, this analysis will be done both on observations directly, and integrated with models to verify how models reproduce variability (and to some extent trends) in ^{13}C, also constraining processes responsible for the land and ocean carbon sinks on decadal to centennial time scales.

j) Attribution of main driver of the land and ocean carbon sink. Using observations alone, it is impossible to attribute the causes of any observed long-term change (e.g. increases in Leaf Area Index (LAI), in seasonal cycle CO_2 amplitude, etc.), Models are needed to "attribute" these changes. As applied routinely for climate variables[92], we will use standard detection/attribution methodologies to attribute the observed changes in the land and ocean carbon cycle and associated water cycle to potential drivers (CO_2, climate, N inputs, land-use, etc. over land; CO_2, climate, winds over the ocean). Attribution methods have been used in the past studies for single observations, such as trend in river runoff[93] or trend in LAI[94]. Here we will include all available carbon-related observations that have a long enough record to allow detection of significant changes, and conduct a series of factorial, single-forcing, model simulations to isolate the processes responsible for the observed changes across all observations. We will quantify the model responses at the process level, using a fingerprint attribution method to compare the simulated and observed temporal and spatial patterns. This will allow us to better identify and constrain the processes related to the land and ocean carbon sensitivity to changes in environmental drivers, primarily atmospheric CO_2 and climate. The global and regional attribution of the land and ocean carbon sinks to long-term changes in atmospheric CO_2 vs. changes in climate is critical for our capability to predict the carbon cycle (and hence the climate response) over the 21st century[8]. By combining the results from all the models in 4C, we will be able to make quantitative probabilistic statements about the causes of land and ocean carbon sinks, equivalent to the attribution statements made by the IPCC concerning the causes of global warming (e.g. "we estimate that x% of the historical land carbon sink is due to changes in atmospheric CO_2").

1.4.2 Develop near-term prediction of the carbon cycle for the coming decade

By the end of the project, we have the ambition to provide robust annual to decadal predictions of atmospheric CO_2, land and ocean carbon sinks and climate response, in order to inform on the possible outcome of the implementation of the UNFCCC compliant anthropogenic emissions (NDCs) in time for the 2023 global stocktake.

Up to now, ESMs driven by CO_2 emissions have been only used for long-term projections[10], but not in the context of near-term decadal prediction. We will move beyond state-of-the-art by attempting for the first time to predict the evolution of the coupled climate-carbon cycle on decadal timescale, with the additional value of using fully interactive emission-driven ESMs. This will allow us to inform on the possible changes in atmospheric CO_2 and climate resulting from both emissions policies and internal climate and carbon cycle variability.

Over the past decade, 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 such predictions that proved skilful at regional scales[95]. 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[96] or the fluctuations in the strength of the North Atlantic sub-polar gyre[97] and the Atlantic meridional overturning circulation[98].

Future near-term climate is the result of two components a) change in atmospheric radiative forcing and b) the natural variability of the climate system. ESMs can be used to simulate historical and future climate by prescribing the radiative forcing based on observed data and future emission scenarios. These simulations do not attempt to phase the model with the observed natural variability of the climate 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 taken into account by continuously constraining the model's solution towards the observed state of the climate through numerical techniques commonly referred to as data assimilation (or nudging, here used as a synonym). Finally, ESMs can be used to perform **near-term climate predictions** where the radiative forcing is still prescribed 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. **Retrospective climate predictions** are near-term predictions of the past climate initialized using only contemporaneous information available at the time of starting the simulation[95]. Here we use near-term and decadal as synonyms.

While these predictions can be performed using state-of-the-art ESMs with a complete description of the carbon cycle, the predictability of the carbon cycle received little attention so far. Thus, the extension of this exercise beyond the physical climate is an emerging and promising topic which has been explored only in a few models so far to investigate the predictability of oceanic primary production over the tropical Pacific[99] or the global ocean[100] and of the carbon uptake over the North Atlantic[101] or the global scale in a perfect model set up[102]. As of now however, no modelling group has attempted ESM-based initialized near-term predictions of the global carbon cycle driven by CO_2 emissions. Furthermore, the only decadal predictions of the climate system planned for CMIP6 are based on a middle of the road greenhouse gas scenario (SSP2.4.5), not highly relevant in the context of the Paris Agreement. 4C will produce unique decadal predictions of the global carbon cycle with state-of-the-art CMIP6+ ESMs driven by near-term NDC compliant emissions, allowing us to develop the capability to assess the success of NDCs implementations in terms of expected atmospheric CO_2 and climate response, accounting for the natural variability of the carbon and climate system, ultimately providing unique policy relevant information for the global stocktake. Such predictions will be important tools to indicate potential early warning of systematic errors in emission reporting, or carbon cycle response.

We will repeat the emission-driven decadal predictions for 3 years of the project, allowing us to produce annual predictions of the following year's global carbon budget (atmospheric CO_2 and carbon sinks). Such predictions have never been attempted before apart from a simple regression previously used to reconstruct atmospheric CO_2 growth rate on the basis of anthropogenic emissions and Equatorial Pacific sea surface temperature anomalies[103], no attempt has been made so far to predict next year's global carbon budget. By repeating these predictions we will compare our results with CO_2 observations in near real time. This exercise will allow assessing and continually improving our representation of the processes driving the carbon cycle sensitivity to climate variability on annual to decadal time scales. This is the first step towards establishing a semi-operational system for near-term prediction of atmospheric CO_2.

To reach these specific objectives, 4C will adopt a step-by-step strategy, progressing from a process-oriented perfect model approach to estimate the potential predictability of the carbon cycle[102], to data-assimilated reconstructions that provide initial conditions for CO_2 concentration-driven near-term predictions and then, finally, for CO_2 emission-driven near-term predictions. Each step is meant to improve some aspect of our understanding of the decadal predictability of the climate and carbon cycle systems as follows:

a) *To understand and quantify the potential predictability of atmosphere-land and atmosphere-ocean carbon fluxes*. A classic way to quantify potential predictability is through a "perfect model approach"[104] in which we assume that the model reproduces all the processes driving the predictability of a given variable and that such representation is not affected by model biases. This potential predictability is a measure of how long the memory of an initial state drives the evolution of a given variable in a given region. Or in other words, it quantifies the ability of the model to predict itself. Such an approach is well suited to establish a theoretical framework of predictability assessment across different models, as well as to investigate and better understand the processes driving predictability of the global carbon cycle.

In our case, the perfect model framework will be used to assess the potential predictability of key variables for the carbon cycle for which we have insufficient observations. This allows for a better understanding of the mechanisms driving low frequency (interannual to multi-decadal) variability of land and ocean CO_2 exchange with the atmosphere. For the ocean, in addition to air-sea CO_2 fluxes, we will focus on its first-order drivers, i.e. sea-surface temperature, surface alkalinity, surface dissolved inorganic carbon, primary productivity, mixed layer depth and ocean circulation. For the land, in addition to land-atmosphere CO_2 fluxes, we will focus on surface air temperature, precipitation, soil humidity and snow cover. The perfect model approach allows discerning the regions and processes that drive the low frequency variability of CO_2 fluxes, as well as providing an estimate of the carbon cycle system predictability horizon in a consistent manner across different models. This information will be crucial for the interpretation of results from both retrospective and future near-term predictions. For instance, if a modelling system has a short potential predictability horizon for air-sea CO_2 flux for a given region, we would treat with caution a future prediction of atmospheric CO_2 variation if such variation were mostly driven from that region.

Previous studies show that the North Atlantic and the Southern Ocean are main contributors to the low-frequency variability of ocean-driven atmospheric CO_2 variations[24,102]. However, the mechanisms behind this variability are of a different nature between the regions. In the Southern Ocean the main driver of interannual to decadal variability in air-sea CO_2 flux is the supply of natural dissolved inorganic carbon (DIC) along the Ekman-driven upwelling region while for the North Atlantic the physical system (sea surface temperature or mixed layer depth variations) seems to have a more direct control[89]. Furthermore, the equatorial Pacific emerges as a critical region for atmosphere-ocean coupling, as well as for controlling the variability of the land carbon surface fluxes and atmospheric CO_2. Different models could give a different picture of the driving processes, pointing to an urgent need for a multi-model assessment as we propose in 4C.

b) *To test initialization techniques for retrospective and future predictions*. The three modelling groups involved in near-term predictions within the project will produce the CMIP6 "historical" (driven by CO_2 concentration) and esm-hist (driven by CO_2 emissions) simulations with the CMIP6+ version of the models (see Tables 1.2 and 1.3), covering the period 1850-2015 (see Figure 5). While the climate of the historical simulations is not necessarily in phase with the observed climate, they provide a good starting point to produce reconstructions where ocean and atmospheric physical fields are nudged to observations to phase the model's climate with the observed variability. We will not directly assimilate any observation for the carbon cycle allowing instead both land and ocean biogeochemical models to evolve following the physical constraints of the ocean and atmospheric forcings. We will let the model's climate adjust to the observations for over two decades (1958-1980) and then consider initial conditions for retrospective near-term predictions.

The reconstructed fields are used as a compromise between the inherently biased model solution and the observed state of climate and carbon cycle. We will test several options for producing the reconstructed fields by varying, for example, the weight of the nudging towards observations. This will translate in several possible solutions for the initialization of the retrospective predictions that we will assess against the observation products elaborated in WP1 (air-sea CO_2 fluxes, ocean interior C distribution, terrestrial water storage, evapotranspiration, land-atmosphere CO_2 fluxes, see Table 1.1b) to compute metrics that will allow highlighting strengths and weaknesses of our reconstructed carbon cycle. Such systematic multi-model exploration of initialization techniques has never been attempted before and will represent a milestone in the establishment of an organized community focusing on near-term predictions of global carbon cycle.

c) *To quantify the predictability of the carbon cycle and climate systems.* We will perform ESM-based decadal retrospective predictions using the initial conditions that best approximate observations among those tested (see point (b) above). At this stage, we will use both CO_2 concentration-driven and newly developed CO_2 emission-driven simulations. The latter will enable us to simulate prognostic atmospheric CO_2 concentrations along with the evolution of land and ocean carbon sinks, therefore accounting for emerging climate-carbon feedbacks and the climate response all together. Retrospective predictions will be bias-corrected following procedures that have been tested and investigated over the past decade in the context of seasonal-to-decadal climate predictability[105]. Our retrospective predictions will be performed every year for the period overlapping the availability of the observation-based products from WP1 (1981-present, see Table 1.1b and Figure 5) to allow for a more meaningful statistical reliability of results, drift treatments, skill assessment, as well as predictive skill assessment.

The predictive skill of the carbon cycle variables, analogous to the physical climate variables, is not geographically uniform. Moreover, predictive skill is decaying with time, being strongest over the first few years during which the effect of initialization is stronger. Therefore, we will particularly target prediction years 1 to 5 and will identify regions with highest prediction skill. For the first time there will be an extensive assessment of the impact of different approaches regarding initialization, ensemble generation, and model architecture across the three ESMs on the prediction skill of the carbon sinks. Of particular interest here is to establish the prediction skill of the ocean and land carbon compartments and test their coherence in a multi-model context. We will also assess the sources and time scales of predictability of the global carbon cycle in the three different prediction systems. The skill assessment for our retrospective decadal predictions will focus on the observation-based products from WP1 (air-sea and air-land CO_2 fluxes; see Table 1.1b), on observations of atmospheric CO_2 in the case of CO_2 emission-driven predictions as well as on climate variables (e.g. surface temperature). It is also useful to assess the prediction skill against the reconstructions (based on the nudged simulation of the ESMs, see above point b). Thereby we will identify potential effects on the prediction skill of data gaps in observational products and gain confidence in our understanding of the time-scales of predictability of the climate-carbon system.

With the new knowledge acquired on the mechanisms responsible for the climate-carbon system predictability and with the improved predictive systems developed during 4C we will attempt to forecast the future near-term evolution of atmospheric CO_2 over the stocktake period using for the first time ever emission-driven ESMs for decadal predictions. These will be performed assuming CO_2 emissions follow NDC ambitions while non-CO_2 emissions will be prescribed according to the sustainability narrative SSP1[99]. These predictions will be compared to “baseline” decadal predictions that use SSP2-4.5 CO_2 emissions and non-CO_2 prescribed concentrations, allowing us to assess the skills to detect and attribute changes in atmospheric CO_2 and climate response due the implementation of the UNFCCC NDCs.

As an absolute novelty, 4C will represent the first step towards establishing a semi-operational system for predictions of atmospheric CO_2 growth rate for the next year, along with estimates of consistent land and ocean carbon sinks, allowing for near real-time evaluation of the predictive skill of our carbon cycle forecast system. This prediction/evaluation will be repeated the last 3 years of the 4C project.

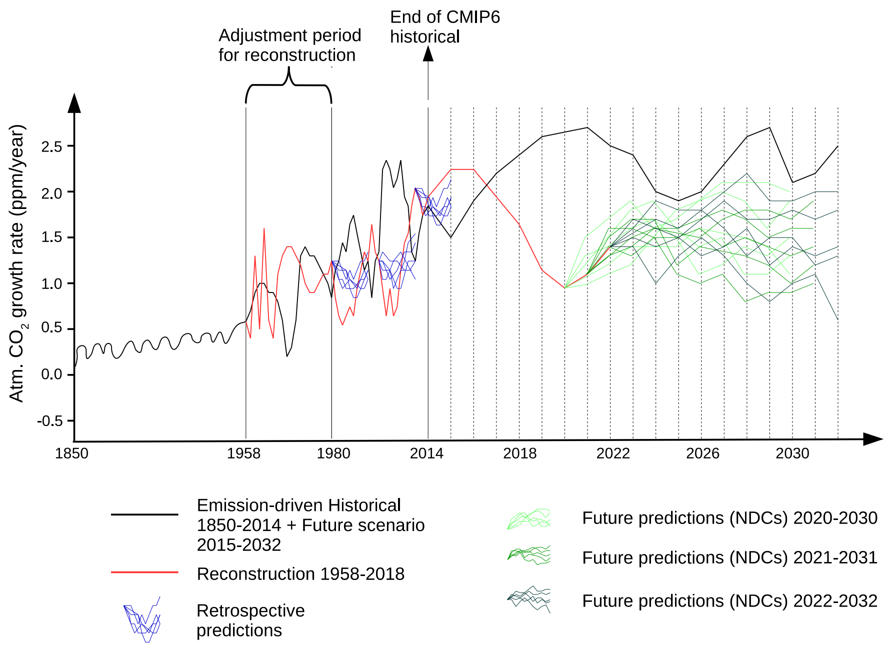


Figure 5. Idealized representation of simulations in WP2. A data-assimilation (i.e. reconstruction) run (red line) is initialized from year 1958 of an historical simulation (black line). The reconstruction requires a period of adjustment to digest the data-assimilation and synchronize its climate to the observed. After this, an ensemble of retrospective predictions is initialized every year from 1981, from the reconstruction run (blue lines, only three start dates are shown). Future predictions are initialized from the last year of the reconstruction and repeated 3 times over the course of the project (green lines).

1.4.3 Reducing uncertainties in climate projections over the 21st century

By the end of the project, 4C has the ambition to reduce the current uncertainty in TCRE by a factor of two.

4C has the ambition to significantly reduce the uncertainty in ESM projections and in particular to provide best estimates of TCRE and the related remaining carbon budget consistent with climate targets. The IPCC AR5 likely range of TCRE (0.8°C to 2.5°C warming for 1000 GtC) is so large that it severely limits its relevance for policymakers (see Figure 3). In striking contrast with equilibrium climate sensitivity (ECS), which has not shown significant progress in reducing uncertainty over the last 50 years[106], we expect to deliver major advances in reducing uncertainty in carbon cycle feedbacks over the period of the 4C project. The crucial difference is that TCRE depends on the Transient Climate Response (TCR) and the airborne CO_2 fraction, both of which being constrained by observations, in contrast to the multi-century adjustments that largely determine the ECS[107].

4C will use two methods to improve our confidence in climate and carbon projections.

First we will develop new emergent constraints on climate-carbon cycle feedbacks, making use of the large set of observations gathered in the project. The emergent constraint framework uses an ensemble of Earth system models to estimate the relationship between a modelled but observable variation in the climate system and a predicted future change. By combining the model derived emergent relationship with the observed variations and their uncertainty estimates, an emergent constraint on the predicted future change can be produced[108]. Building on our previous work[109-111,35], we will further develop new emergent constraints on carbon processes using new observations (e.g. xCO_2, SIF, terrestrial water storage, CFCs, SF_6, etc.). We will also develop emergent constraints on new processes included in CMIP6+ ESMs. For example, we will explore the potential for emergent constraints on future carbon release from fire, using the observed biomass burning interannual variability[76] and historical trend[112], and on permafrost carbon loss using the observed spatial distribution of permafrost and observed carbon storage[109]. These estimates will be particular important for scenarios compatible to 1.5 and 2°C where the remaining carbon budget is very limited.

Second, we will use our large set of carbon cycle and related observations (e.g. water and energy cycle) to assess the CMIP6 ESMs skills at simulating the observational record. For constraining the simulated land carbon uptake, we will employ C-cycle benchmarking with the ESMValTool, including recent satellite-based estimates and reconstructions of global terrestrial water storage[34], evapotranspiration[111], SIF and other proxies for GPP, satellite and in situ atmospheric CO_2 measurements, as well as observational constraints related to nutrient limitation, wildfires, such as burned area[47] and permafrost processes[74]. For constraining the ocean carbon uptake, we will use observations of air-sea CO_2 [24], ocean interior carbon[39] and tracers (CFC-11, CFC-12, SF_6) measurements, the seasonal cycle of the surface ocean carbon systems. In 4C, we will combine these skills with newly developed emergent constraints to further weight CMIP6 model projections, reducing uncertainty on future atmospheric CO_2, carbon sinks (and associated impacts), and climate projections.

4C will also develop new adaptive climate scenarios tailored to adequately support the Paris Agreement ultimate goal to limit warming to 1.5 to 2°C. These adaptive simulations, combined with 4C model skills assessments and new emergent constraints, will provide the optimum remaining carbon emissions consistent with the ambitions of the Paris Agreement.

a) TCRE and carbon budgets in the context of the Paris Agreement

One source of uncertainty in AR5 estimates of TCRE was the use of different methods to estimate it, involving either observations (with multiple uncertain forcings) or ESMs forced with 1%/per year increasing CO_2 and diagnosed emissions (in which forcing is known, but not clearly relevant to ambitious mitigation). Since AR5, further work has emerged documenting the scenario-dependence of the TCRE[113,114], but uncertainties arising from very high cumulative emissions or long adjustment timescales are not necessarily relevant to limiting warming to well below 2°C in the second half of this century. Under 4C, we will focus on quantifying uncertainties in TCRE that are directly relevant to ambitious mitigation pathways by diagnosing it directly using ESMs from these scenarios in CMIP6. TCRE can be diagnosed from a multi-gas emission scenario using CO_2-forcing-equivalent (CO_2-fe) emissions. This is an old concept[115] whose effectiveness (and considerable advantages over the more widely-used CO_2-equivalent emissions) for the analysis of ambitious mitigation scenarios was recently demonstrated[37], allowing the concept of TCRE to be applied directly to multi-gas scenarios. CO_2-fe emissions will be diagnosed from CMIP6 integrations, using the native CMIP6 carbon cycle models (diagnosing CO_2-fe emissions requires expressing total anthropogenic as an equivalent concentration of CO_2 and then inverting the model's carbon cycle to diagnose the emissions required to generate this forcing as if it were entirely of CO_2 origin). A hypothesis that we will test is that the fractional uncertainties in the CO_2-fe emissions budgets consistent with 1.5°C or 2°C of warming diagnosed in this way is lower than that those implied by of the full range of estimates of TCRE estimated from multiple methods and scenarios. If this hypothesis proves correct, we will argue that this lower range of uncertainty is more relevant to carbon budgets for ambitious mitigation than the TCRE defined as in AR5.

b) Weighting models for more robust projections

The reliability of projections from a large ensemble of models might be improved if models are weighted according to some measure of skill, or if only subsets of models are considered[116]. This process includes the development of techniques for the generation of probabilistic predictions by statistical processing of ensemble integrations. The easiest approach to multi-model combination is to assign the same weight to each model. In this case, the spread between equally forced models at longer projection time scales is related to the total model uncertainty; however, this spread does not reflect systematic biases in the models. Alternatively, different weights are assigned to the individual models, with weights reflecting the respective skills or the confidence we put into them. The underlying assumption is that the reliability of a large ensemble can be improved giving greater weights to 'better performing' models. So far there is no consensus on what is the best method of combining the output of several climate models, thus none of these methods has yet won widespread acceptance. In WP3 we will compare projections from the un-weighted multi-model ensemble to different weighting schemes and test the robustness of weighting approaches considering both model performance and interdependence[117,118] while fully exploiting observations from WP1 and considering their uncertainties.

c) Adaptive scenarios to meet the Paris Agreement ambition

4C will develop new climate scenarios tailored to support the Paris Agreement ultimate goal to limit warming to 1.5 to 2°C. AR5 or CMIP6 scenarios are not ideal to support to UNFCCC as they prescribe greenhouse gases emissions (or concentrations) at the outset, independent of the climate response. Hence, a model with a large TCRE would likely exceed the climate target while a model with a low TCRE would likely remain below, implying that it would have allowed slightly larger emissions. 4C will develop new adaptive scenarios where the anthropogenic emissions prescribed to the ESM are revised every 5 years, depending on the remaining warming before meeting a climate target, mimicking the periodic stocktake process. These adaptive simulations, combined with 4C models' skills assessments and new emergent constraints, will constrain remaining carbon emissions consistent with the ambitions of the Paris Agreement.

1.4.4 Improved process understanding and representation in ESMs

4C has the ambition to significantly improve our understanding of land and ocean processes controlling the evolution of atmospheric CO_2 over the historical record, assessing their predictability in the near-term and their control on long-term projections via their interaction with the climate system. Over the course of the 4 years of the project, 4C will consolidate the recent process-level developments in ESMS, and will be repeated on an annual basis, the sequence of (a) historical simulations, (b) confrontation against a growing set of observational constraints, (c) improved understanding of dominant processes at different time-scales, and d) further developments and parameterisations of carbon components in ESMs. This constant benchmarking against reality will force model developers to reassess their model's skill continuously during the 4C project. This virtuous circle can only benefit our understanding of the key biogeochemical feedback processes in ESMs, improving our confidence in near-term predictions and long-term projections and their relevance for policymakers.

Likewise, 4C will attempt to predict the atmospheric CO_2 and carbon sinks for the coming year, using the first year of our decadal predictions. This will allow us to test in near-real time our capability to anticipate natural variability of the climate-carbon cycle system. Similarly to weather and seasonal forecasts, the systematic confrontation in near real time of model prediction to actual observations can only help improving processes representations and our predictability skills on annual to decadal time scales.

1.4.5 Communicating our results to a broader audience, including policymakers and the larger public.

4C aims to synthesise, and disseminate its scientific findings to foster a broader understanding of climate-carbon interactions and accurate interpretation in support of scientific assessments and policymaking. In addition to the standard scientific dissemination of results (scientific publications and conferences) there is a pressing need for a wider contextualisation of the research findings to support scientific assessments such as IPCC, IPBES and the Global Carbon Budget. 4C will develop, use and promote ScienceBrief, an innovative ICT platform, unique of its kind, that helps scientists and people interested in science to keep up with rapidly-emerging scientific findings. ScienceBrief allows the scientific community to post and interpret new publications that support or contradict the current consensus (e.g., as defined by IPCC Assessment Reports). ScienceBrief Carbon Cycle is the first pilot of ScienceBrief, championed by 4C investigators with the active contribution as Editorial Board members from five lead authors of the IPCC AR6 (https://sciencebrief.org/topics/carbon). It will be launched in late 2018. We will use ScienceBrief to support the integration of 4C results with existing science, to help identify knowledge gaps, emerging consensus and new controversies, and to guide timely research.

As well as ScienceBrief, as explained in more details in section 2 –Impact–, during the entire lifetime of the project a range of actions and tools are envisaged with the goal of enhancing knowledge transfer targeting different audiences and positioning the project and its partners as Subject Matter Experts of reference in the topic. Emerging scientific consensus will be translated into usable formats for policymakers (e.g., fact sheets explaining main findings, carbon outlooks, ad hoc events and a policy brief) and into easy-to-grasp information for the larger-audience (e.g., communication content for platforms, animated infographic, explorable explanations, posters) with particular attention to the visualization of the quantitative content.

The ultimate goal of the communication and dissemination activities it to ensure the long-lasting impact of the project on society by creating usable knowledge and enhancing the interactions between scientists and stakeholders, which will help build trust and usage of the results.

A key output of 4C is to contribute to the Global Stocktake process of the UNFCCC. In addition to our contributions to AR6, this will involve holding side-events at the UNFCCC annual COP and SBSTA meetings. The Global Carbon Project has a well-established track record of well-attended and high profile events on which we can build, providing opportunities to discuss with both Parties and Observers how emerging science on the carbon cycle can best contribute to the stocktake.

2 Impact

2.1 Expected impacts

4C will contribute to the four key impacts mentioned in the topic:

- supporting major international scientific assessments such as the IPCC;
- increase confidence in climate change projections;
- providing added-value to decision and policymakers; and
- sustaining Europe's leadership in climate science.

2.1.1 Support major international scientific assessments such as the IPCC

a) Development of appropriate support: 4C partners have extensive experience in assessment reports, particularly the IPCC, and are aware of many of the challenges in performing assessments. A growing challenge is processing and assessing the expanding scientific literature, including literature that may emerge during the IPCC writing and review process. To concretely address this challenge, 4C will further develop the tool ScienceBrief in WP4 to prepare the project outputs, and associated literature, for scientific assessment. ScienceBrief links emerging literature to key assessment findings (key statements) to determine whether the literature supports, modifies or refutes a statement, and over time builds a case for improving key statements. This provides a practical tool for IPCC authors and reviewers. The further development of this tool will ensure that 4C can feed smoothly and directly into the IPCC AR6, a crucial factor given the strict AR6 timelines relative to the project timeline. Post-AR6, and for other relevant scientific assessments, ScienceBrief will provide a solid foundation from which to start the assessments.

b) Involvement in IPCC: The extensive experience and involvement of 4C partners in IPCC assessments will be important to support international scientific assessments. Previous experience helps to inform what information is needed to undertake assessments, while the current involvement ensures direct input into the assessment process. Both points are crucial to ensure input into AR6, with the literature deadline early in the 4C timeline. 4C involvement in IPCC assessments (as coordinating or lead authors) is as follows:

- Previous: IPCC SAR (Joos); IPCC TAR (Joos, LeQuéré); IPCC AR4 (Ciais, Cox, Friedlingstein, Le Quéré, Joos); IPCC AR5 (Bopp, Brovkin, Ciais, Cox, Eyring, Friedlingstein, Le Quéré, Doblas-Reyes); SREX (Seneviratne).
- IPCC AR6: the 4C consortium contributes 12 scientists in all three working groups and all special reports: WG1 (Brovkin, Cox, Eyring, Seneviratne, Zaehle, Doblas-Reyes), WG2 (Bopp), WG3 (Peters), SR1.5 (Allen, Seneviratne), SROCC (Frölicher, Gruber); SRCCL (Davin).

c) Involvement in International Scientific bodies: The high international standing of the 4C consortium will ensure our work is communicated across the main international science bodies closely tied to international assessments, contributing to on-going research, as well as engendering new studies. 4C partners include the chair of the WCRP/CMIP Panel (Eyring), co-chair of the WCRP/ Modelling Advisory Council (Doblas-Reyes), co-chair of Future Earth/AIMES (Brovkin), chairs of the WCRP/Grand Challenges 'Carbon feedbacks in the climate System' (Friedlingstein and Ilyina) and 'Weather and climate extremes' (Seneviratne), incoming member of the WCRP Joint Scientific Committee (Friedlingstein) and members of WCRP Working Group on Coupled Modelling (WGCM) (Eyring, Friedlingstein). Moreover, 4C counts SSC members of key CMIP6-Endorsed Model Intercomparison Projects: ScenarioMIP (Eyring, Friedlingstein), AerChemMIP (Eyring), C^4MIP (Friedlingstein, Bopp, Brovkin, Ilyina, Zaehle), LUMIP (Brovkin, Seneviratne), LS3MIP (Seneviratne), DCPP (Doblas-Reyes) and OMIP (Bopp, Ilyina). 4C also includes former chairs and members of GCP (Le Quéré, Ciais, Friedlingstein, Peters), and the leadership team of the GCP Global Carbon Budget (Le Quéré, Peters, Friedlingstein, Sitch, Ciais).

2.1.2 Increase confidence in climate change predictions and projections

Climate projections assessed in IPCC AR5 had large uncertainty on carbon cycle feedbacks, in part due to the lack of observational constraints, leading to unconstrained climate-carbon feedbacks and an unacceptably broad range in policy relevant indicators such as the TCRE and remaining carbon budgets. 4C will aim to reduce these uncertainties, by confronting ESMs with novel observations over the last 60 years, with a focus on the recent past where observations are stronger. By focusing on short- to medium-term projects (1-10 years), the predictive skill of ESMs can be assessed, and future projections improved by emerging constraints and weighting. The EMSs used in 4C will include processes not fully included at the time of CMIP6 simulations, such as nitrogen and phosphorous limitation on land, permafrost carbon on land, high resolution physical transport in the ocean, and explicit upper trophic and bacterial degradation as well as variable stoichiometry in marine ecosystems, all potentially controlling the strength of carbon cycle feedbacks. The early stages of 4C will feed into improved understanding for AR6, but 4C will lay the foundations for the next generation of ESMs feeding into AR7 and informing the Paris Agreement's Global Stocktake process.

4C will also produce and update new adaptive scenarios where emission pathways are revised every five years to be consistent with recent warming trends. The regularity is designed to link to the Paris Agreement's Global Stocktake process, and the methodology ensures that policy relevant indicators (e.g., required rates of mitigation, remaining carbon budgets) are consistent with the latest evolution and understanding of the climate system.

2.1.3 Providing added-value to decision and policymakers

4C will provide added-value to decision and policymakers in two key ways. First, through improved science that feeds into the policy process (section 2.1.2 above), and second, through enhanced knowledge transfer. The enhanced knowledge transfer is managed in WP4 and covers 1) scientists, 2) decision and policymakers, and 3) the broader public. T4.2 of WP4 is specifically focussed on adding value to decision and policymakers. Our approach in T4.2 is to translate existing and the new knowledge (from 4C, but also other projects) into a language that facilitates an effective dialogue with decision and policymakers. Several tools will be used to achieve an effective dialogue. We will initially prepare decision and policymakers for the information to come by providing fact sheets on the core concepts to be investigated in 4C. Building on this, 4C findings will be translated into usable formats (e.g., executive summaries, policy brief), which also put the findings in context with other emerging literature. These targeted contents will be communicated in several formats (text, info-graphics, etc.). In addition, carbon outlooks will build on the annual release of the Global Carbon Budget to present annual and decadal forecasts developed in 4C. To ensure that fact sheets, executive summaries, and the chosen format is relevant, we will maintain close dialogue with decision and policymakers through our extensive networks to ensure interaction with scientists and allowing for bi-directional exchange of ideas.

2.1.4 Sustain Europe's leadership in climate science

4C will include the main European climate modelling groups and the leading European groups on carbon cycle science. 4C will uniquely secure Europe's leadership in Earth System science by developing new observation-based constraints on carbon fluxes, building and using next generation ESMs developed in Europe. These ESMs with augmented representation of biogeochemical processes will provide an improved understanding of the carbon cycle and climate interactions for the contemporary, near-term predictions and long-term projections. 4C will also secure European leadership, developing the unique capability to perform near-term predictions from prescribed CO_2 emissions, and long-term projections following adaptive scenarios. 4C also has a near balanced mix of research institute and university based partners, training PhD students and postdoctoral level young scientists, thereby nurturing the next generation of European climate scientists.

2.2 Measures to maximise impact

Dissemination and exploitation activities are of high importance both during the project – to create visibility, influence and raise awareness within the stakeholder communities – as well as legacy after the project – to utilise the project results, find ways to further continue and advance the related research and pave the way for future exploitation of the project's achievements. Our dissemination activities target a wide audience, with a strong focus on scientists (e.g., assessments), policy and decision makers, and the broader range of other interested audiences. The measures to maximize impact aim to:

- Enhance the uptake of 4C science in international reports
- Maintain the contribution of high quality EU science to this field
- Position the ScienceBrief platform among trusted science-based evidence providers
- Engage in trusted science-based evidence discussions with decision- and policy-makers
- Foster mutual learning between policymakers and scientists.

The dissemination, exploitation, and communication strategies are briefly discussed in this section as three distinct but complementary approaches:

The **dissemination strategy** aims to position the scientific results, tools and knowledge from the project to be usable by a range of stakeholders within science and society contributing to the development of relevant national, European, and International policies.

The **exploitation strategy** aims to provide a framework, so the scientific results produced within the project have continuity after the end of the project funding period.

The **communication strategy** aims to raise awareness, create visibility and support dissemination and exploitation by providing a strong visual identity, media tools and channels, as well as fostering linkages with other projects and programmes.

2.2.1 Dissemination and exploitation of results

The 4C team has extensive experience in interacting with high-level decision and policy makers, particularly building on the annual high-profile releases of the Global Carbon Budget and wide-ranging involvement in the IPCC process (see section 2.1.1). Interactions have been at the scientific level (e.g. IPCC), negotiations level (e.g. UNFCCC, SBSTA), with national policy makers (e.g. government ministries and departments), and with journalists. The dissemination, exploitation and communication strategies are coordinated through WP4, and are led by highly-experienced organizations with extensive experience in policy and decision makers' engagement and dissemination: BSC (WP4 lead), CICERO (WP4 deputy lead), UEA (WP1 lead), UNEXE (coordinator) and UOXF. These institutions will be supported by the contribution of relevant partners to foster linkages with the scientific-driven WPs.

Dissemination

A range of dissemination tools will be used and will be tailored to the needs of the various stakeholders and audiences relevant for the project.

The identified actions for dissemination of the project's results are the following:

- **4C workshop for fast-track support to IPCC AR6:** This workshop will be organised with 4C's IPCC lead authors to facilitate consultation with 4C researchers on how to address the issues raised on the ongoing draft and identify key issues for Post-AR6 assessments.
- **ScienceBrief platform:** This platform will be improved and used to disseminate scientific outputs from 4C -and other scientific activities- for incorporation into international scientific assessments.
- **Fact sheets:** We will present the main concepts to create a knowledge base to better understand the outcomes of 4C science.
- **Executive summaries:** We will ensure key project results are communicated in a format appropriate for decision and policymakers by preparing science summaries from relevant deliverables.
- **Carbon outlooks:** These outlooks will be released annually in partnership with the GCP Global Carbon Budget with focus on the forecasts of the full year carbon budget and an assessment of previous year's forecasts.
- **Side-events for policymakers:** Events will be organised in parallel to major policy gatherings, such as international climate negotiations (e.g., UNFCCC COP and SBSTA side-events).
- **EU policymakers' workshop:** This event will be organised in Brussels to promote the interaction between scientist and stakeholders.
- **Presentation at conferences, symposia, meetings:** 4C partners will attend key climate conferences (e.g. EGU General Assembly (annually), International Carbon Dioxide Conference in 2021) as well as upcoming workshops relevant to 4C science (eg. CMIP6 related workshop).
- **Policy brief:** We will present the most relevant results together with an overview of current policies on emissions and a set of policy recommendations towards the end of the project.
- **Publication of papers in high-profile journals:** We will target gold open-access dissemination in journals such as Nature Geoscience, Nature Climate Change, etc. Several partners also have additional institutional practices in place to comply with green open-access requirements, such as via institutional and organisational repositories of published papers (for example, Open Research Exeter, see https://ore.exeter.ac.uk/repository).

4C will pro-actively collaborate with other projects and institutions to meet its dissemination objectives. An example will be the close collaboration with the highly successful annual release of the Global Carbon Budget or the synergies with the Global Carbon Atlas to disseminate fact sheets, infographics, etc. Effective coordination and communication with other national, European and international activities will be achieved through partners' involvement in relevant ongoing activities (See Table 2.1) and will build on recent and current EU funded initiatives involving 4C partners such as: CRESCENDO, EMBRACE, HELIX, VERIFY, C-CASCADES, EUCP, PRIMAVERA, APPLICATE, CarboChange, GreenCyclesII, etc. In particular 4C will communicate with VERIFY and the CONSTRAIN and other projects funded under the same call as 4C. 4C will benefit from the new satellite XCO_2 algorithms developed under VERIFY and the annual carbon budgets produced in VERIFY. Synergy with CONSTRAIN will come from their strong focus on quantification and constraints on the equilibrium climate sensitivity (ECS).

Table 2.1 Synergies with international committees and steering groups.

Partner	**International Project / International Committees**
Friedlingstein (UNEXE)	Co-chair CMIP6/C4MIP, member CMIP6/ScenarioMIP Co-chair WCRP/Grand Challenge on carbon cycle Member of the GCP Global Carbon Budget core team Member WCRP/ Joint Scientific Committee (starting 01/2019) ScienceBrief Carbon Cycle co-Chair
Sitch (UNEXE)	Member of the GCP Global Carbon Budget core team Co- lead of TRENDY international land model intercomparison project
LeQuéré (UEA)	Lead, annual publication of the Global Carbon Budget Co-chair of the GCP Global Carbon Budget core team Ex-officio member, Global Carbon Project Member, UK Committee on Climate Change (advises the UK government) ScienceBrief Director
Bopp (ENS)	Member CMIP6/C4MIP and CMIP6/OMIP, Member IMBeR (Future Earth)
Ilyina (MPG)	Co-chair WCRP/Grand Challenge on carbon cycle Member CMIP6/C4MIP and CMIP6/OMIP
Brovkin (MPG)	Co-chair AIMES
Zaehle (MPG)	Member CMIP6/C4MIP
Seneviratne (ETHZ)	Co-chair CMIP6/LS3MIP, member CMIP6/LUMIP Co-chair WCRP Grand Challenge on Extremes
Doblas-Reyes (BSC)	Co-chair WCRP/WMAC, member CMIP6/DCPP, member EU-ENES HPC task force
Eyring (DLR)	Chair WCRP/CMIP panel Member WCRP/WGCM and Climate model diagnostic and metrics panel Member CMIP6/ScenarioMIP and CMIP6/AerChemMIP Member WCRP/Data Advisory Council's Observations for Model Evaluation
Joos (UBERN)	Member CMIP6/OMIP, PAGES Carbon Peat Working Group, PAGES Ocean Circulation and Carbon Cycling Working Group ScienceBrief Carbon Cycle co-Chair
Peters (CICERO)	Ex GCP SSC, Co-chair of the GCP Global Carbon Budget core team
Allen (UOXF)	Member CLIVAR/International Detection and Attribution Group
Ciais (CEA)	Member of EC Copernicus task force on carbon observing system Member of the GCP Global Carbon Budget core team

Exploitation of results

The models and tools created by 4C will continue to feed into and enhance European climate change research:

WP1 synthesis of carbon cycle observations can be used to keep evaluating future new developments of ESMs. New methods and metrics developed in WP1 and WP3 will be made available to the whole scientific community through the ESMValTool[1] a community diagnostics and performance tool for the evaluation of Earth System Models. The GCP Global Carbon Budget will be able to use 4C methodology to incorporate information derived from other elements (Oxygen and ^{13}C) to strengthen the reliability of future carbon budget estimates.

WP2 will release decadal predictions of atmospheric CO_2 and carbon sinks which will be delivered in time to inform the global stocktake in 2023 and the following ones after the end of the project. Most importantly, WP2 will also work towards establishing a semi-operational system providing annually next-year predictions of the climate-carbon system. The aim is to actively work during the project to find the appropriate platform to release

[1] https://www.esmvaltool.org/

these predictions also after the project. A possible platform, for instance, would be the multi-model decadal forecast exchange initiative[2] led by the MetOffice.

WP3 will develop new process-based emergent constraints on the biogeochemical cycles also made available to the community via the ESMValTool. Further, WP3 will develop new methodologies and climate simulations following the concept of adaptive scenarios, providing a theoretical framework for climate projections in line with the Paris Agreement ambitions.

WP4 will contribute to promote and position ScienceBrief[3] as a coordinated activity, building consensus around Carbon cycle scientific statements relevant for IPCC post-AR6 assessments. Further, WP4 aims to increase the understanding of the carbon cycle, and its uncertainties, amongst policy and decision makers, and the general public.

4C will build on previous and successful activities such as the mentioned Global Carbon Project, ScienceBrief and ESMValTool. Equally, all the results of 4C incorporated to these initiatives will be fully exploited after the end of the project. 4C is committed to continue research after the end of the project and to continue the exploitation of the results produced within the project. We also have the ambition to strengthen the 4C network to expand the research agenda in climate-carbon cycle interactions resulting in future potential funding opportunities.

Research Data Management

The project will generate data including observation-based data products for the global carbon cycle (Table 1.1b), historical, near term and long-term ESM simulations (Table 1.3). We will preserve and make these data available in accordance with the EC's Open Research Data pilot. An open data policy will ensure transparency of data and models generated within 4C. The Coordinator will be responsible for the management of the research data throughout the life of the project, supported by the PI from each partner. Individual researchers will be responsible for creating the supporting documentation, which will be written at the time the data is created. Documentation will be regularly checked for accuracy and consistency. Version control will be used. This will include a version control table on the front page of each document produced. Our data standards will ensure that all new data generated by 4C is compliant with the data standards established in the community, such as CMOR format. Each partner, using their own data centre, will store the original data locally. All observation-based data generated in the project (Table1.1b) will be stored on a 4C server at the University of Exeter, which provides secure, backed up network storage. Once the project is complete and any IP has been protected, these data will be archived in the University's Institutional Repository, Open Research Exeter (ORE). The Data Management Plan will be detailed by month 6 (Deliverable 5.2) and updated in sync with reporting periods (M18, M36). The Data Management Plan will also detail how the data will be generated, documented (metadata), made accessible, curated and preserved.

Personal data and GDPR compliance

4C will pay special attention to the personal data and will gather explicit consent to collect and manage this information. For internal communication, the personal data of project partners will be needed to ensure the collaboration and normal functioning of the project in all work packages. For the dissemination of the research results, personal data from stakeholders will be used to facilitate user engagement and maximise the dissemination of the project outcomes. We will obtain consent to keep participant contact details, which will be used to invite them to take part in future research or to tell them about the results of the project. Personal data might be collected through different types of actions such as: project mailing lists, website contact form, carbon outlooks subscription, online surveys, and e-mail contacts with stakeholders interested in 4C events. The personal data managed in this project are only related to professional information (name and surnames, position, institution and contact information). Besides professional information, during the events planned along the project lifetime pictures and videos could be taken, always with the informed consent of the people recorded. Sensitive personal data will not be requested (i.e. membership in a religious or political group, sexual orientation, etc.).

Knowledge management and protection

4C will follow the guiding principles of Horizon 2020 on Intellectual Property (IP) management. The precise details for how IP will be handled (including details of IP ownership, access rights to any Background and Foreground IP for the execution of the project and the exploitation of results, the protection of intellectual property rights (IPRs) and confidential information etc.) will, as is normal practice, be formulated in the

[2] https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/decadal-multimodel
[3] https://sciencebrief.org/

Consortium Agreement. Other important components for the good management of IP rights will be directly handled by WP5 and the technology transfer offices of the partner institutions. This Consortium Agreement will be signed by all partners before the project start date. The management support team (MST) and the General Assembly (GA) will monitor the potential exploitable results of the partners to safeguard timely data, knowledge and information generated in the project will any attached rights including protection of IP.

2.2.2 Communication strategy

Our communication activities aim to increase the visibility of 4C project and our external communication strategy will draw on the principles outlined in the H2020 Guidance Document 'Communicating EU research and innovation guidance for project participants'.

Our outline communication plan, below, will be formalised in the Communication, Dissemination and Exploitation Plan (CDEP) to define the goals and objectives of communication and to provide a full framework for the development of communication tasks during the lifetime of the project detailing target audiences, communication tools and channels, key messages and practical information such as branding project style, logo, guide, templates, etc. This plan will be a live document revised and updated at least twice during the project lifetime.

All dissemination and communication activities will be monitored and followed-up to maximize their impact and reported at the end of the project. Table 2.2 presents the initial communication and dissemination plan.

The dissemination actions listed above will be complemented and enhanced by communication channels and tools described here:

- **Project webpage:** A user friendly website with easy navigation will be set up for both public and consortium member's access. The website will be actively maintained during the lifespan of the project. It will give different audiences access to the project's facts and figures, published periodic activity reports, a summary page on progress and achievements and also to downloadable publishable presentations, leaflets and PDF files of journal publications as well as to press releases and other media outputs.
- **Project brochure and leaflets:** These PR materials, both printed and particularly on-line, will be created for the wider, non-specialized scientific community and stakeholders. They will be created and distributed to partner's institutions, EC and at dissemination events. These could eventually include also PDF versions of the policy brief, science summaries, etc.
- **Frequently Asked Questions (FAQ):** On the 4C webpage there will be a FAQ board, where an initial set of questions will be posted. Any question arisen during engagement activities will be transformed in a new question in the FAQ page.
- **Web based explorable explanation:** this interactive application will rely strongly in the visualisation of quantitative information and it will serve as supporting material for researchers to present the project to EU officers and other stakeholders. It will have a user-friendly interface and modern appealing graphic design, thus, it should be equally effective for dissemination to the general public as well.
- **Social media tools (Twitter, LinkedIn, YouTube):** Instead of putting resources into specific 4C social media accounts, we will build on the existing networks of 4C participants and use the hashtag #4C when relevant.
- **Press releases and media tailored material:** Press releases will be written and circulated to relevant media list whenever there is a newsworthy topic. Initially, press releases will be written in English although translated versions (Spanish, French, German) may be created by project's partners to target national media.

Table 2.2 4C communication and dissemination activities by target audiences

Target audience	Activities	Objective	WP. Task
4C consortium	• Project portal to share files • E-mail updates/mailing lists • General Assembly	• Monitoring against work plan • Facilitate internal communication • Share knowledge • Detect and address internal risks • Maximise impact and dissemination	5.1
Scientific community **International scientific assessments**	• Scientific publications • Presentations at conferences • Collaboration with IPCC authors • Sciencebrief platform	• Share knowledge • Dissemination of scientific outcomes • Maximise impact and exploitation • Foster maximum societal benefits	4.1
EU decision and policy makers **Intergovern-mental organisations**	• Fact sheets, leaflets, executive summaries, policy brief • Carbon outlooks • Workshops, Presentations at conferences • Web explorable explanation • Face to face meetings	• Position the project partners as Subject Matter Experts of reference • Share practical implications of the scientific results • Maximise impact and exploitation • Foster maximum societal benefits	4.2 4.3 4.4
Other Stakeholders	• Fact sheet, executive summaries • Carbon outlooks • Web explorable explanation • Social media activity	• Position the project and its partners as Subject Matter Experts of reference • Maximise impact and exploitation • Foster maximum societal benefits	4.2 4.3 4.4
General public	• Fact sheets, Science summaries • Outreach activities • Social media activity • Project website, FAQ • Web explorable explanation	• Ensure visibility of the climate-carbon topic • Ensure the topic is reliably communicated • Share practical implications of the scientific results	4.3
Media	• Press releases • Op-eds and other contents • Direct communication • Social media activity • Fact sheets, Science summaries	• Ensure broad visibility of the project • Position the project partners as Subject Matter Experts of reference for journalists	4.3 4.4
Other projects and initiatives in the topic	• Project website • Leaflet, executive summaries • Workshops, Presentations at conferences • Social media activity	• Promote clustering • Share knowledge • Maximise impact and exploitation • Find synergies with other initiatives to co-organise events and actions	4.1 4.2 4.4 5.1
EC Project officer and Policy officer	• General assembly • Periodic reports • Fact sheets, policy brief, executive summaries • Workshops	• Ensure EC is fully informed of overall project progress	4.2 4.3 4.4 5.2

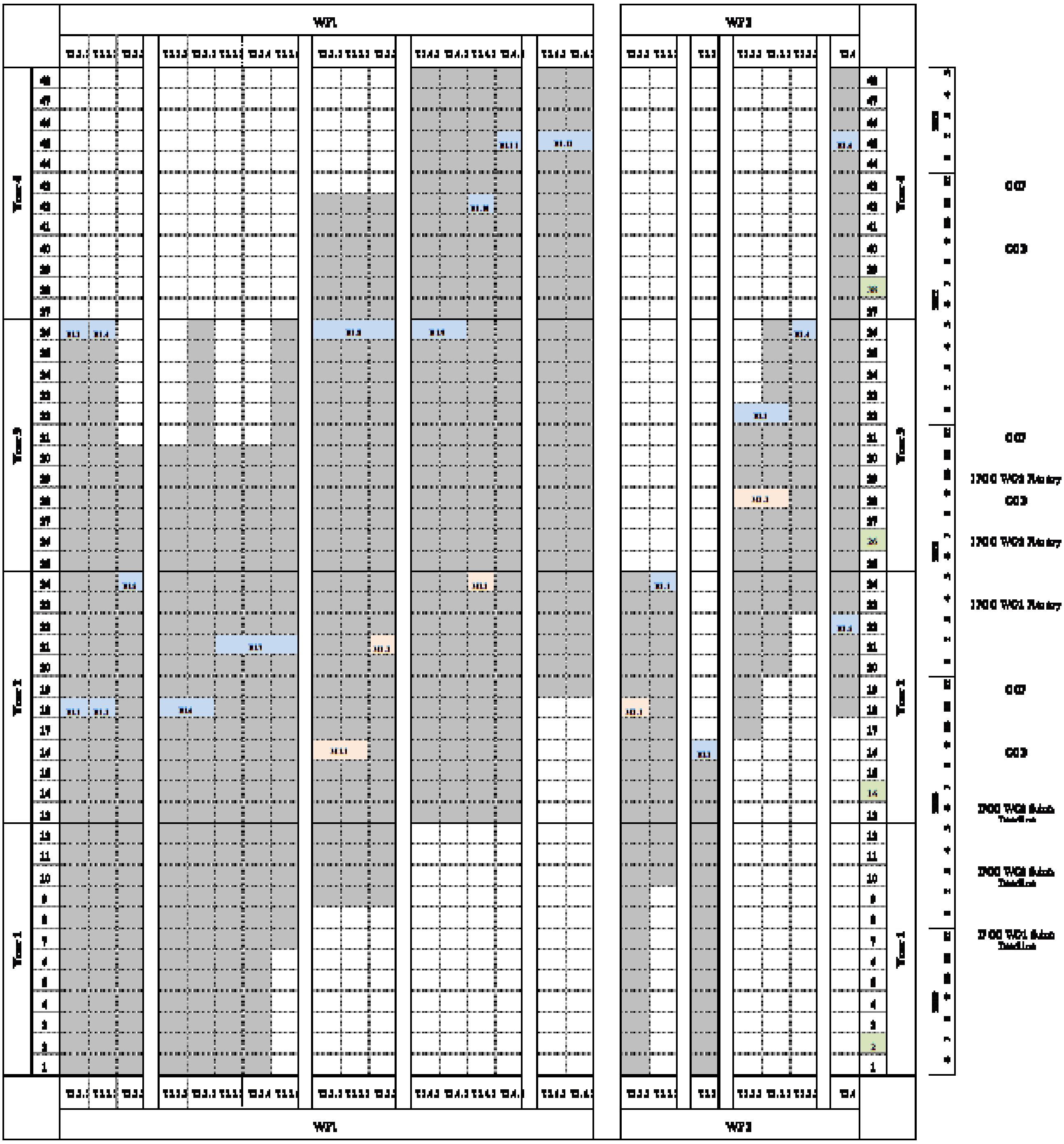
3 Implementation

3.1 Work plan

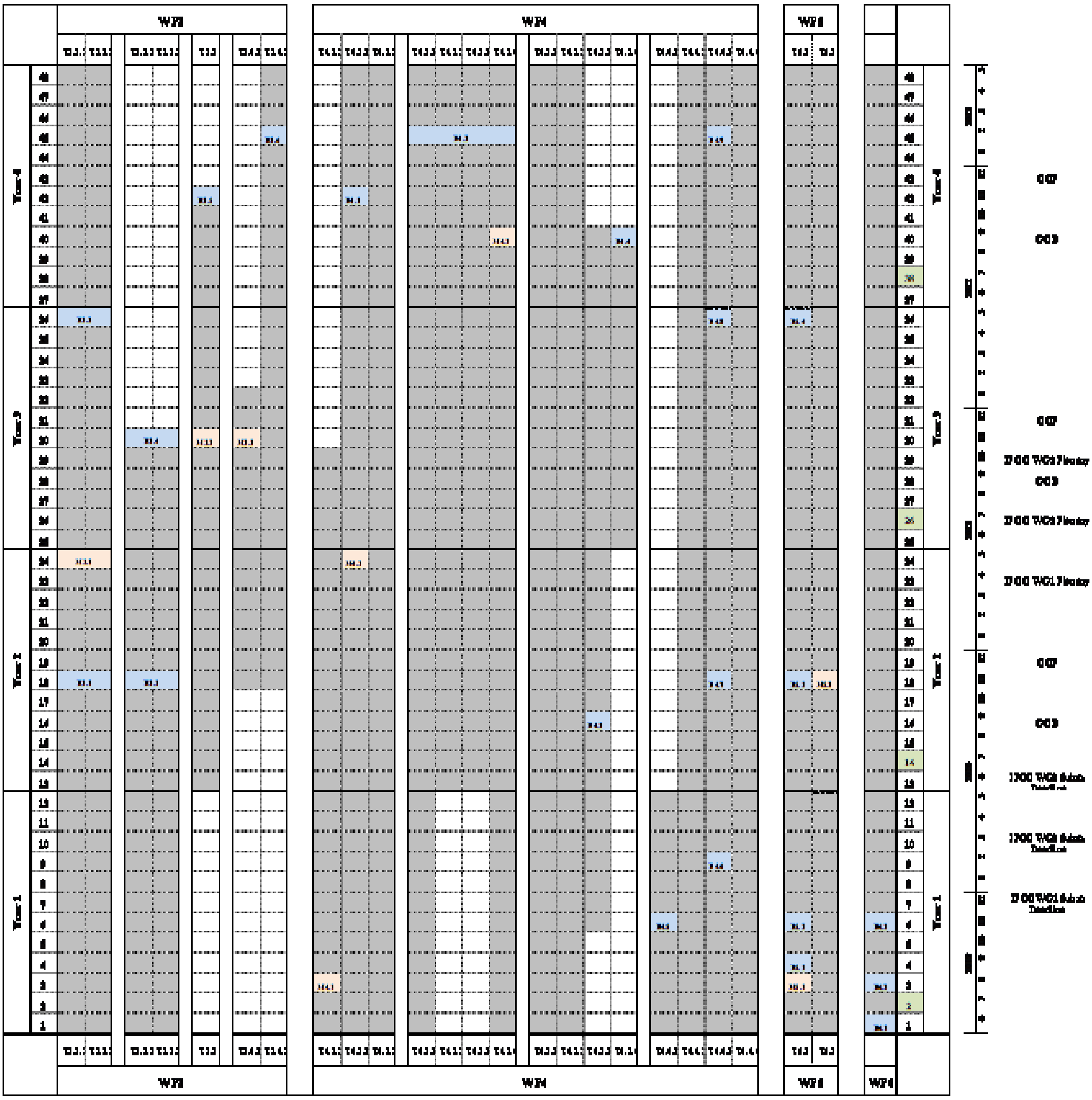
3.1.1 Overall structure of the work plan

4C is organised in six work packages. WP1 to WP3 are scientific WPs, each addressing one overall scientific objective of 4C. WP4 is devoted to synthesis and dissemination of the outcomes of the whole project, WP5 is devoted to the project management and WP6 considers ethical issues. The choice of having three relatively large science WPs was driven by the wish to ensure efficiency and close interactions between the project partners. Therefore, each work package is divided into a comprehensive set of tasks, with, in most cases, specific subtasks. Each WP involves several partners, has well defined goals, and has clear linkages with the other WPs (see Figure 4, section 1.3, and project Gantt chart below). Given the broad ambition of each WP, we assigned two WP leaders (a WP lead and a deputy lead), each task having a lead partner identified.

3.1.2 Project schedule



WP1-2 4C project Gantt chart with WP tasks and subtasks length (grey cells), timing of deliverables and milestones (blue and orange cells), and tentative timing of annual meetings (green cells). Timing of key stakeholders activities is also given at the bottom.



WP3-6 4C project Gantt chart with WP tasks and subtasks length (grey cells), timing of deliverables and milestones (blue and orange cells), and tentative timing of annual meetings (green cells). Timing of key stakeholders activities is also given at the bottom.

3.2 Management structure and procedures

Work Package 5 addresses project management and is designed to ensure the smooth operation of the project in terms of day-to-day management, decisions at the milestones, production of deliverables and liaison with the European Commission. The project management procedures, including IPR issues and decision-making procedures will be formalized in the Consortium Agreement, which all partners will sign prior to the signature of the Grant Agreement. The aim is to achieve:

- A management structure that incorporates scientific, technical and partner coordination as well as issues of normal business operation;
- Procedures that respect the dedicated research commitment of the entire team;
- Rapid and efficient decision making close to the responsible level of execution;
- Reliable and trusted agreements to protect intellectual properties of all partners and encourage sharing and collaboration.

3.2.1 Overall management structure

The main components of the management structure of 4C are:

- The **Coordinator**, who will lead the project and be the intermediary between the consortium and the European Commission and be supported by a **Management Support Team** (**MST**) to ensure the overall day-to-day project management and administration, in close collaboration with the Work package leads.
- The **General Assembly (GA)**, the overarching decision-making body which is responsible for the project's major strategic, scientific and technological policies.
- The **Executive Board (EB)** implements the decisions taken by the GA and monitors and ensures the project's overall progress, and consists of the Project Lead and the WP leads.
- The **Work Package Leaders** ensure the day-to-day project management and administration of each work package.
- The **External Advisory Board (**EAB). Each EAB member will adhere to and sign specific terms of reference at the start of the project, including confidentiality clauses when relevant.

The Coordinator and Management Support Team (MST)

The Project Coordinator is UNEXE, represented by Prof Pierre Friedlingstein as Project Lead. The Coordinator's primary role is to represent the Consortium to the European Commission (EC) and to take overall responsibility for ensuring that the project meets its objectives. The Project Coordinator is responsible for project coordination including the scientific and technical quality-control of deliverables, as well as the planning, administrative and strict financial follow-up of the project.

The Project Coordinator will be responsible for:

- organising and chairing the GA and EB and ensuring that any relevant issues are brought to the attention of these governing bodies;
- ensuring smooth operation of the project: work plan maintenance, project progress monitoring, analysis of the results, identification of problems and consequences for future research;
- overseeing the preparation and quality of the project's progress reports and deliverables;
- submitting all required progress reports, deliverables and financial statements to the EC;
- communicating all relevant project information to the EC and acting as intermediary between the EC and the project partners;
- handling payments to the partners and transferring sums in a timely manner, in line with the provisions of the Consortium Agreement and the decisions of the GA;
- organising meetings of the External Advisory Board;
- management of risk and challenges during the course of 4C;
- promotion of the Consortium’s activities for the potential cooperation with similar initiatives/projects.

The Management Support Team will be composed of Prof Pierre Friedlingstein (UNEXE) and of a project manager employed by UNEXE. Support from UNEXE professional services teams including a dedicated EU team consisting of experienced specialists in the management and financial delivery of EU projects, Legal and IP specialists will be available to the MST.

The MST will be in charge of day-to-day project management, administration, and logistics across the project, including:

- Communication of all information in connection with the project to the Commission;
- Preparation of the project deliverables and delivery to the Commission, after validation by the EB;
- Day to day co-ordination of the project; monitoring project planning and progress,;
- Communication within the project, to partners, governing bodies, users, and the general public;
- Organisation of meetings and internal reviews;
- Preparation of the quality control, data management and documentation plan;
- Co-ordination and collaboration with other EU–funded or other international projects;
- Overall administrative and financial management,
- Management of consortium-level legal and ethical issues
- Liaising with the EAB and preparing their meetings

The Project Manager will assist the Project Coordinator in the day-to-day monitoring of the project, supporting communication with project partners and the project governing bodies, keeping track of project deadlines, issuing reminders to project partners, checking on follow-up of planning schedule, etc. S/he will maintain the internal project communication instruments, providing mailing lists, online resources for files sharing, and setting up teleconferences and webex meetings as needed. S/he will assist the Project Coordinator in the preparation of the deliverables, milestones and periodic reporting to be submitted to the Commission. The Project Manager will also assist the Project Coordinator with finance reporting and in any financial actions between the Commission and the project partners.

The General Assembly (GA)

The GA is the overall decision-making body of the consortium and will include one representative from each partner. The GA will be chaired by the project coordinator and supported by the Management Support Team. The GA will be responsible for validating the major decisions concerning the project. It is the decision-making body for any issue concerning the proper operation of the consortium and will resolve any project disputes arising between partners that cannot be resolved at a lower level. Any partner may request discussion and vote by the PGB on any decision taken previously by the EB or the MST, which could be contrary to its interests.

The matters to be acted upon by the General Assembly include:

- Strategic orientation of the project;
- The Consortium work plan and plans for using and disseminating knowledge;
- The Consortium budget and financial allocation of the EU's contribution between research and dissemination activities on the one hand, and between the beneficiaries on the other;
- Annual validation of the realised expenditure in accordance with the budget;
- Changes in the Consortium membership;
- Determination of a defaulting partner;
- Any major reallocation of budget between partners;
- Any alterations to the Consortium Agreement;
- The acceptance of new beneficiaries as well as any exclusion of beneficiaries;
- Any premature completion or termination of the project;
- Adherence of the Consortium to Open Access requirements and appropriate data management.

Decision-making: The GA's decisions will require 2/3 of the members to be present to be quorate and require a 2/3 majority vote. The decision and problem resolving process will be defined in detail in a Consortium Agreement, which will be signed by all beneficiaries prior to the start of the project.

Frequency of Meetings: In addition to an initial kick-off meeting, the GA will be held once a year, unless intermediate meetings are in the interests of the project. In such a case, the GA will be convened by the Coordinator or when requested by at least 50% of the assembly's members. The MST will operate the GA's secretariat.

The Executive Board (EB)

The Executive Board (EB) is in charge of the day-to-day management of 4C scientific progress of the project, ensuring it stays in line with its scientific objectives and providing early warning of potential scientific or technical issues, allowing implementation of appropriate measures to reduce the risk of delay or delivery of the project objectives. The EB will be the body where discussions will take place and decisions will be made with respect to the work undertaken within and between work packages. The EB is chaired by the Coordinator and comprises all the WP leaders and deputies. Major decisions or recommendations made by the EB which change either the scientific or financial direction of the project must be agreed upon by the GA.

The EB responsibilities include:

- Report on progress of their WPs at four-monthly meetings and through short written reports;
- Providing progress reports on the delivery of the project to the GA;
- Review the project deliverables prior to their submission;
- Consider recommendations from the External Advisory Board (EAB);
- Propose any necessary or beneficial changes of the project budget/membership to the GA;
- Propose and implement the competitive selection procedure for new contractors;
- Make proposals to the GA for any change in consortium membership;
- Lead the proper conduct of the project to maximise outputs and impacts.

The MST will provide support to the EB for these tasks and to write technical and financial reports.

Decision-making: The EB's decisions require 2/3 of the members to be present to be quorate and require a 2/3 majority vote. Each member represented on the EB will have one vote. In case both the WP leader and its deputy are present, only the vote of the WP leader will count.

Frequency of Meetings: the EB will meet every 4 months (unless intermediate meetings are in the interest of the project) either physically or by phone/video conference in order to review project progress, consider any risks related to the WPs and, as required, identify solutions and/or alternative options. The EB will work interactively using a dedicated project intranet and audio-visual tools maintained and provided by the Management Support Team. At least one meeting per year will be face-to-face, organised at the same time as the annual General Assembly.

Work Package Leaders and their Teams

The WP teams are composed of one WP leader, a deputy leader and several other partners (Table 3.2.1). The activities of each WP are subdivided into Tasks that will be conducted by one or more of the Partners. The overall organisation of the Tasks will be supervised by the individual WP leader who will be responsible for the following activities:

- Organising regular internal communication between the WP Participants for Task-related information, documents, planning and deliverables;
- Sending technical, administrative and financial reports (including the Progress and Final Reports) to the Project Coordinator;
- Producing the WP-related deliverables and their submission to the Project Coordinator according to schedule;
- Conducting the initial evaluation of the scientific and technical content of the deliverables;
- Providing the content for the Progress and Final Reports;
- Identifying, in a timely fashion, any potential risk or conflict, any delay or difficulty that might alter the quality and/or the achievement of deliverables, and inform the Project Coordinator and Project Manager;
- Resolving as far as possible any conflict within the Work Package.

The WP team members will be responsible for the following activities:

- Participating in regular internal communication with the WP Leader;
- Delivering the sub-task results and administrative and financial reports to the WP Leader on schedule;
- Providing the content for the Progress and Final Reports;
- Informing their WP leader of any potential risk or conflict or any delay or difficulty that might alter the quality and/or the achievement of deliverables.

Table 3.2.1 WP leads and deputy lead

WP1 lead	Corinne LeQuéré (F)	UEA
WP1 deputy lead	Stephen Sitch (M)	UNEXE
WP2 lead	Tatiana Ilyina (F)	MPG
WP2 deputy lead	Raffaele Bernardello (M)	BSC
WP3 lead	Thomas Frölicher (M)	UBERN

WP3 deputy lead	Veronika Eyring (F)	DLR
WP4 lead	Isadora Jimenez (F)	BSC
WP4 deputy lead	Glen Peters (M)	CICERO
WP5 lead	Pierre Friedlingstein (M)	UNEXE
WP6 lead	Pierre Friedlingstein (M)	UNEXE

The External Advisory Board (EAB)

The EAB will be composed of 6 to 8 experts in the field, covering a wide range of expertise on climate and carbon cycle science, oceanic and land expertise, modelling and observation, science and dissemination (Table 3.2.2). The central role of the EAB is to provide an external, independent critical evaluation of the work done in 4C. The EAB will:

- Advise on the project scientific work plan and outcomes
- Advise on the project dissemination and interface with users
- Provide a perspective and advice on potential links with on-going international activities relevant to 4C
- Suggest potential new developments and actions to further increase 4C scientific outputs and dissemination.

The EAB will be invited to attend the 4C Annual General Assembly, and will be asked to provide feedback and advice during the follow-up EAB meeting. The EAB will submit a written report to the MST within the following 2 weeks. The MST will distribute the EAB report to the project consortium and will propose responsive actions if necessary.

Frequency of Meetings: The EAB will meet annually, physically (preferred option) or remotely. The project's budget includes a line to cover the travel and subsistence costs of EAB members invited to attend project meetings and events. Each EAB member will be required to sign a confidentiality agreement. The Consortium Agreement will fix in detail the governance rules and procedures for the EAB.

Table 3.2.2 External Advisory Board composition

ClaudiaTebaldi (F)	NCAR, Boulder USA	Climate modelling, scenarios
Pep Canadell (M)	GCP, Canberra, Australia	Global carbon cycle, IPCC
Mat Williams (M)	University of Edinburgh, UK	Land carbon cycle, observations
Martin Heimann (M)	Univ. Helsinki, Finland	Global carbon cycle
Leo Hickman (M)	CarbonBrief, London, UK	Communication & outreach
Michio Kawamiya (M)	Jamstec, Yokahoma, Japan	Ocean carbon cycle, ESM
Kirsten Zickfeld (F)	Simon Fraser Univ. Canada	Climate modelling, TCRE

Project gender balance

In the current project structure, 4 of the 6 WPs are led (3) or co-lead (1) by women and approximately 37% of the key personnel involved are female (see section 4). The Project Coordinator along with the Management Support Team will gather statistics and monitor the number and role of women within 4C and take actions if needed.

Gender issues will be tackled by 4C through the following actions:

- Fostering equal opportunities policies that encourage the recruitment of women at equal scientific or technical merit.
- Implementing actions (working-time flexibility, setting of e-conference tools to limit travels and organising predictable travels and meetings) to support male and female researchers with children or other dependants.
- Ensuring that meeting programs, high profile presentations (keynote talks at conferences) are planned from a gender balance perspective.

4C will endorse the principles of the European Charter for Researchers and Code of Conduct for the Recruitment of Researchers.

3.2.2 Appropriateness of the organisational structure and decision making mechanisms

The consortium consists of 12 partners from 6 different EU member states thus it requires an experienced Project Coordinator to successfully manage all of the technical, financial, legal and administrative aspects.

Aside from the organisational structure defined in the previous section, which will ensure an efficient project performance, several processes are highlighted below:

***Management guidelines*:** Management guidelines will be set up at the beginning of the project and will provide all project partners with practical information on project implementation (including a full contact list and a project time line) and templates for project deliverables and reports. The objective of these guidelines is to ensure top-quality project outcomes (meetings, reports, deliverables, dissemination material, etc.) and a common understanding of all project procedures and tools.

***Project document repository*:** A secured intranet system will be implemented at the start of the project and will be restricted to the 4C members. This tool will act as a repository for all project documents, such as contractual documents, minutes of meeting, working documents shared within partners, etc. It is intended to foster collaboration between 4C partners at all levels: WPs, governance bodies, advisory groups, etc.

***Web conference tool*:** Virtual meetings will have an important role in ensuring good information flow within the project and enabling frequent collaboration within the 4C governance bodies and within and between WPs, while minimising travel costs and CO_2 emissions. The MST will provide a tool for GA, EAB and EB meetings and ensure that the web meetings' minutes are uploaded to the intranet for access by all consortium members.

***Quality Assurance*:** Measurable and verifiable results are defined in the workplan in connection with deliverables and milestones. All draft deliverables will be subject to internal quality review before they are accepted as deliverables for submission to the EU. The review process will be two-stage. The first stage will comprise a review carried out by the Executive Board. The second stage of quality review will be carried out by the project coordinator. Only once deliverables have passed both stages of review will they be deemed suitable for submission to the EU. A quality assurance plan will be produced as a deliverable of the project.

***Consortium Agreement*:** A Consortium Agreement (CA) will be signed before the project commences. The University of Exeter coordinates several H2020 project and has therefore substantial experience in developing Consortium Agreements. The CA will be based on the DESCA model and will include:

- The organisation of the consortium, including resolutions of issues, as described above.
- The financial distribution on the basis of each participant's effort and activity type.
- Procedures for changes in the consortium composition.
- IPR and exploitation, including definition of the background brought by all participants
- Rights and rules for joint ownership, access rights to project results for participants and 3rd parties
- Rights and rules for managing appropriate dissemination, respecting ownership and potential confidentiality/embargo.

3.2.3 Innovation Management

The major outputs of this project will be novel data products and model simulations that will be made available to the scientific community. The MST and the EB will monitor the publications and public disclosures of the partners to safeguard the timely distribution of knowledge to the scientific community with any need for protection of IP rights. The nature of the project is such that we do not foresee a need for IP protection. However the EB will review any internal or external opportunity for exploiting the project results when such opportunity arises and an expert from the IP department of UNEXE may advise the partners if necessary during the course of the project should any foreground IP need to be protected. Background IP will remain the property of the project partners.

3.2.4 Critical risks and risk mitigation measures

The overall responsibility for the risk management of 4C will reside with the Project Coordinator supported by all members of the Consortium and the Advisory Board. Risk Management will consist of the identification of risk; its assessment; and response. Risk identification will be a proactive Task for the entire 4C Team as well as within the framework of the WP activities. The EB will be responsible for the assessment and the response. Their risk assessment will qualify the potential impact(s) on 4C, ranking the risk according to low, medium, or high likelihood and minor, moderate or major impact on project delivery. The response to these various risks will be graded in proportion to their degree.

- **Minor risks** can be addressed by the Project Coordinator/Project Manager/WP Leaders;
- **Moderate risks** need to be carefully addressed by the EB and the relevant Partners. Continued forward monitoring and possibly additional adjustments will be necessary;

- **High risks** need to be carefully addressed by the EB, with support by all Partners, potentially also involving the EAB. An agreed upon strategy will be put in place to solve the issue with on-going monitoring, possibly followed by additional measures during which the Project Officer will be consulted.

The critical risks relating to 4C project implementation and the associated risk mitigation measures are listed in ***Table 3.2b***. A risk management plan will be prepared as a deliverable of the project.

3.3 Consortium as a whole

4C will bring together 12 academic partners from seven European countries, with the strongest expertise on global carbon cycle and climate system both from the observation and modelling side. 4C will combine unique expertise on:

- observations and synthesis of global atmospheric satellite CO_2 (UBREMEN), atmospheric O_2 and ^{13}C (UEA, UBERN), ocean surface and interior carbon (MPG, ETHZ), oxygen and isotopes (UEA, MPG, ETHZ, UBERN), remote sensing-based land surface hydrology (ETHZ), atmospheric-based land surface productivity (UNEXE, MPG, CEA);
- global modelling of land (UNEXE, MPG, BSC, UBERN, CEA), ocean (UEA, ENS, MPG, ETHZ, BSC, UBERN) and full Earth System (ENS, MPG, BSC, UBERN, UOXF, CEA);
- realisation of ESM simulations in the context of CMIP5 and CMIP6 (ENS, MPG, BSC, CEA)
- analysis and intercomparison of simulations of the global carbon cycle (UNEXE, UEA, ENS, MPG, ETHZ, UBERN, CEA)
- evaluation of carbon cycle models (UNEXE, UEA, ENS, MPG, ETHZ, UBERN, CEA), climate models (MPG, BSC, UOXF, DLR, UNEXE, UBERN, ENS, CEA)
- development of evaluation tools such as ESMValTool (UNEXE, DLR, UBREMEN, MPG, CEA)
- emergent constraints on the carbon cycle and climate system (UNEXE, ENS, ETHZ, DLR, UBREMEN, CEA)
- emission scenarios and climate response (UNEXE, ENS, MPG, UBERN, CICERO, UOXF, CEA)
- synthesis, dissemination and interaction with policymakers and end-users (UNEXE, UEA, BSC, CICERO, UOXF, CEA).

The consortium is a balanced mix of leading European process-parameterization developers in land and marine biogeochemistry, all working closely with physical model development scientists at each of the modelling centres. The strong involvement of European experts on land and atmospheric, land and ocean carbon observations, synthesis and use for process understanding, together with model developers will ensure a process-based ESM evaluation and improvement.

The consortium has seven research institutes, and five university-based partners, all with demonstrated experience in the training of PhD students and postdoctoral level young scientists, nurturing the next generation of European, which we view as an important aspect of the project.

The ESM groups in the 4C consortium are all experienced in executing major international coordinated simulations (such as for CMIP5 and CMIP6) and delivering data in a structured manner (CMOR format) onto the Earth System Grid Federation (ESGF). Further many of the partners are already working together successfully in current H2020 projects on ESM development (CRESCENDO, PRIMAVERA) or greenhouse gases budgets (VERIFY), and have a long history of working together in past project, such as the H2020 HELIX, C-CASCADES, and the FP7 EMBRACE, CarboChange, GeoCarbon, GreenCyclesII and COMBINE projects.

The 4C consortium also includes a number of groups (BSC, UEA, CICERO, CEA, UNEXE) with extensive experience in science communication directed towards key groups such as policymakers, but also general interested public, and academic disciplines. Particularly relevant here, the consortium has more than 10 years of experience in delivering the science and communication on the annual global carbon budgets in the context of the UNFCCC activities. This will ensure 4C will maintain a high-quality activity in communication/dissemination with both policy and public arenas (see WP4).

As detailed in section 2.1 the consortium includes numerous past or current IPCC authors, as well as members of WCRP programs and Future Earth core projects, including the CMIP panel chair (Eyring, DLR). The consortium also includes leaders of six Model Intercomparison Projects (MIPs) that are part of CMIP6 and its contribution to the IPCC AR6 (see Table 2.1). This type of representation will ensure 4C science is well represented at international levels and being informed of international plans in global carbon and Earth system science. Reporting on the involvement with these committees and groups need to be done in the 4-monthly EB meetings and progress report with the EC EASME Project Officer.

Two of the ESMs used and improved in 4C are originally developed by two major US Earth system modelling centres (GFDL and NCAR), ensuring strong interactions with these groups and the US ESM community.

Our External Advisory Board (EAB) is deliberately of international dimension and trans-disciplinary, covering areas such as Earth observations, carbon cycle and climate process understanding, ESM development and evaluation, science-policy advice and science communication.

We believe the 4C consortium contains the necessary expertise to realize our ambitious science objectives, while also being sufficiently cross-disciplinary to successfully interact with major complementary areas of Earth system science and maintain a high-quality dialogue with both policymakers and the public. Furthermore, the consortium will ensure 4C science influences Earth system science well beyond the conclusion of the project; through the training of Early Career Scientists, the improved understanding of the contemporary carbon cycle perturbation and the provision of key state-of-the art Earth system near-term predictions and long-term projections in support of the Paris Agreement.

3.4 Resources to be committed

Table 3.4b: 'Other direct cost' items (travel, equipment, other goods and services, large research infrastructure)

Not applicable to any 4C partners

4 Members of the consortium

4.1 Participants (applicants)

Partner name: University of Exeter (UNEXE)
Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal
The University of Exeter is one of the leading universities in the UK, a member of the UK's Russell Group and ranked in the top 100 universities worldwide (Times Higher Education). UNEXE is a member of the prestigious Russel Group of UK research-intensive universities, and recipient of the Sunday Times University of the Year award for 2012-2013. It has more than 18 000 students, and more than 2000 academic staff. The University has a dedicated European office to advise and help with research management. UNEXE has strong experience in European Commission-funded research; the EU portfolio consisted of 158 projects in the European FP7 programme, leading on twelve large collaborative grants such as this one and 118 H2020 projects including leading on 63 projects, eight of which are large collaborative grants. The portfolio also includes 30 live ERC grants (including an ERC Advanced to Prof Cox) and 46 Marie Curie projects (33 of which they lead). Strategic commitment to interdisciplinary climate change research is demonstrated by recent investment of £6M and 18.5 new academic staff Our world-class team of global change researchers (e.g. 6 lead authors of IPCC AR5) collaborate closely with the Met Office, making Exeter a centre of expertise for global biogeochemical cycling & climate science. Current University plans include the development of a new Global Systems Institute uniting a trans-disciplinary group of researchers, educators and partners to look beyond single 'environmental' issues to a truly systemic view of coupled global changes in the human social and economic sphere and the biosphere. The University plans to invest in the GSI to recruit over 30 more academic posts and create a flagship building at its Exeter campus, built and operated using the highest sustainability principles. It will house 75 principal investigators and 375 researchers, research students and visiting fellows who will also have access to state-of-the-art learning spaces and facilities. **Role in the project:** UNEXE will coordinate the 4C project, and contribute to all WPs. UNEXE will contribute to historical simulations and evaluation for the land carbon with the JULES model, and will lead Task 1.5 on the carbon sinks attribution. UNEXE will also contribute to WP3 analysis of carbon feedbacks and developments on new emergent constrains for land processes. UNEXE will have a strong involvement in 4C dissemination (WP4) and will be in charge of the project management (WP5)
Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities
Professor Pierre Friedlingstein (M) [4C Project Coordinator] is a UK Royal Society Wolfson Research Merit recipient; he is Chair in Mathematics of the Climate System in the College of Engineering, Mathematics and Physical Sciences. He has more than 25 years research experience in global carbon cycle and climate modelling and is author of over 150 peer-reviewed publications, including 40 in high-profile journals. He is a Highly Cited Researcher in Geosciences since 2014. He co-leads the coupled climate carbon cycle intercomparison project (C4MIP), part of the CMIP6 project, directly feeding in the IPCC 6th assessment report. He is the co-chair of the Grand Challenge "Carbon Feedbacks in the Climate System" under the World Climate Research Programme (WCRP). He is member of the Working Group on Climate Modelling (WGCM) of WCRP as is past member of Global Carbon Project (GCP). He has been actively involved in climate assessment through his participation in the Intergovernmental Panel on Climate Change (IPCC) since 1994. He was lead author for the IPCC Fifth Assessment Report for both Working group I and for the Synthesis Report. He is co-I of several EU projects on Climate and Earth System Science (CRESCENDO, EMBRACE, PAGE21, HELIX, LUC4C). **Professor Stephen Sitch (M)** [4C Task 1.4 Leader] holds a Chair in Climate Change, with 25 years research experience in Earth System Science. He was principal developer of the LPJ model, the World's most highly

cited Dynamic Global Vegetation Model (DGVM), and has been theme leader of community experiments, plant physiology, vegetation and disturbance of the Joint UK Land Environment Simulator, JULES, the land component of the UK Earth System Model (UKESM). He was contributing author for the last 3 IPCC reports. He co-leads TRENDY (with Prof Friedlingstein), the international activity providing land flux estimates from an ensemble of DGVMs for the Global Carbon Project's (GCP) annual carbon budget update, and GCP's Regional Carbon Cycle Assessment and Processes (RECCAP) phases 1 and 2. Prof Sitch is included in Thomson Reuters' 2014 list of the world's most influential scientific minds in environment and ecology and Highly Cited Researcher in Geosciences in 2017. He is co-I on several recent EU projects on Climate and Earth System Science (HELIX, and WP lead on LUC4C).

Professor Peter Cox (M) [4C WP3] is Professor of Climate System Dynamics at the University of Exeter. His expertise is in the modelling of interactions between the land biosphere and climate change. Prof Cox led the team that carried out the first climate simulations to include the carbon cycle and vegetation as interactive components, and he has recently pioneered the development of emergent constraints on climate-carbon feedbacks. He is a lead author on the 4th, 5th, and forthcoming 6th Assessment Report of the *Intergovernmental Panel on Climate Change*, is a member of the UK *Defra Science Advisory Council*, and has been named as a *highly-cited author* in Geosciences by Thomson-Reuters 2014-2017. He is co-I of the EU CRESCENDO project and holds an ERC Advanced Grant ('ECCLES', 2017-2022).

Leo de Sousa-Webb (M) [4C Project Manager] is a Training Manager within the STEMM Cluster at the University of Exeter, and member of the Climate Dynamics Research Group and Exeter Climate Systems (XCS). He is a Chemistry and Mineral Engineering graduate with 15-year experience in project management as a PRINCE2 practitioner, and managed or supported recent EU projects on Climate and Earth System Science (C-CASCADES, CRESCENDO, ECCLES, LUC4C and C-LEAK).

Carolina Duran-Rojas (F) [4C Software engineer] joined the University of Exeter Climate System Group in September 2017 as a Software Engineer, providing support to JULES (Joint UK Land Environment Simulator) users at the University of Exeter and collaborating with scientist at the Met Office in developing the JULES model. Previously, she worked as a Statistics Tutor at the University of Exeter and at the Bath Spa University. She previously worked at the National Observatory of Mexico as a Support Astronomer, and as a post-doctorate at the Institute of Astrophysics of Andalusia located in Granada, Spain. In 2009, Carolina completed a PhD, a Master of Science in Astronomy in 2004 at the National Autonomous University of Mexico (UNAM) and a Degree in Physics and Maths at the University of Michoacan, Mexico.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, et al. (2018), Global Carbon Budget 2017, Earth System Science Data, vol. 10, no. 1, pp. 405-448.
2. Millar, R., Fuglestvedt, JS, Friedlingstein, P, Rogelj J, Grubb MJ, Matthews HD, Skeie RB, Forster PM, Frame DJ, Allen MR, Emission budgets and pathways consistent with limiting warming to 1.5 C (2017) Nature Geosciences, DOI: 10.1038/NGEO3031
3. Peters GP, LeQuéré C, Andrew RM, Canadell JG, Friedlingstein P, Ilyina T, Jackson RB, Joos F, Kosbakken JI, McKinley GA, Sitch S, Tans P (2017), Towards real-time verification of CO_2 emissions, *Nature Climate Change*, doi:10.1038/s41558-017-0013-9.
4. Chadburn, S.E., Burke, E.J., Cox, P.M., Friedlingstein, P., Hugelius, G., Westermann, S. An observation-based constraint on permafrost loss as a function of global warming (2017) Nature Climate Change, 7 (5), pp. 340-344. DOI: 10.1038/nclimate3262
5. Wenzel, S., Cox, P.M., Eyring, V., Friedlingstein, P. Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO_2 (2016) Nature, 538 (7626), pp. 499-501. DOI: 10.1038/nature19772

5 relevant previous projects or activities, connected to the subject of this proposal

1. CRESCENDO, H2020 2015-2020 (Co-Is Friedlingstein and Cox), which will progress the next generation of European Earth Systems Models by improving the representation of key processes in the models; evaluating the scientific performance of these models; using the models to generate a new set of Earth system projects for the coming century and ensuring that the knowledge developed is communicated to key stakeholders.
2. TCRE1.5, NERC 2016-2018 (PI Friedlingstein) which investigated the relationship between cumulative CO_2 emissions and global warming. In particular we assessed what is the carbon budget compatible with a warming of 1.5°C, as estimated by Earth System Models, but using the historical observational record as a way to constrain the relationship between cumulative carbon dioxide emissions and global mean warming. The project found that a remaining budget of about 250 GtC (approx. 23 years of current emissions) is compatible with a climate stabilisation under 1.5°C.
3. ECCLES, ERC 2017-2022 (PI Cox), which is designed to produce significant reductions in the uncertainties associated with land-climate interactions, using the novel concept of Emergent Constraints - relationships between future projections and observable variations in the current Earth System that are common across the ensemble of ESMs.
4. HELIX, FP7 2013-2017 (Co-Is Friedlingstein and Sitch), which assessed the potential impacts of climate change by developing a number of future scenarios of the natural and human world as a consequence of 1.5°C, 2°C, 4°C and 6°C global warming.
5. LUC4C, FP7 2013-2017 (Co-Is Friedlingstein and Sitch) which sought to advance our fundamental knowledge of the climate change - land use change interactions, and develop a framework for the synthesis of complex earth system science into guidelines that are of practical use for policy and societal stakeholders.

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

The University of Exeter maintains its own cluster of Linux computer, including local data storage facility. has access the UBERN Linux Cluster and, maintains within the Oeschger Centre two one Petabyte data storage facility. UNEXE has access to JASMIN the UK High Performance Computing Infrastructure (http://www.jasmin.ac.uk/) as well as the associated Centre for Environmental Data Analysis (CEDA) for storage of large datasets. This will allow UNEXE to perform model simulations (WP1 and WP3), and to store 4C key results for common analysis. The University of Exeter also has a Digital Team, responsible for the University's external-facing web and digital presences.

Partner name: University of East Anglia (UEA)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The University of East Anglia is one of the longest established interdisciplinary institutions of its kind in Europe. In the last assessment of universities in the UK (REF2014), the School of Environmental Sciences was ranked 1st in the UK for 'impact', with 88% of its research judged world leading or internationally excellent. The School has been awarded the Queen's Anniversary Prize for Higher and Further Education in 2017, for 50 years of ground-breaking environmental science at UEA. The Royal accolade from the Queen is the UK's most prestigious higher education award, demonstrating outstanding work at a world-class level. The School's researchers have expertise in climate data and analysis, particularly through its Climatic Research Unit (CRU), and physical and biogeochemical oceanic processes and observations.

The Tyndall Centre at UEA is the headquarters of a network of UK universities founded in 2000. Researchers at the Tyndall Centre conduct cutting edge, interdisciplinary climate change research, and provide a conduit between scientists and policymakers. The Tyndall Centre has since 2000 significantly advanced the fundamental analysis of emission reduction from all major energy sectors, the understanding of climate impacts, risks, and adaptation options, the public perceptions of climate change, and the governance of climate negotiations and policymaking.

4C work at UEA will be collaborative work between the School of Environmental Sciences and the Tyndall Centre.

Role in the project: UEA will lead WP1 on historical carbon budget, contribute the development on new observational constraints (O_2 ,APO and ^{13}C), perform, and evaluate historical simulations with the NEMO-PlankTOM10 ocean carbon model at standard and high-resolution, also contributing to the attribution analysis. UEA will have a strong involvement in WP4, in particular UEA chairs the ScienceBrief platform and will ensure its contribution to the project dissemination, in particular to IPCC and policy-makers.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Prof Corinne Le Quéré FRS (F) [4C WP1 co-lead and Task 4.1 lead] is Professor of Climate Change Science and Policy at UEA. She has more than 25 years of research experience in carbon cycle analysis and modelling, occupying previous research positions at Princeton University in the US, the Max-Plank-Institute for Biogeochemistry in Germany, and the British Antarctic Survey in the UK. She instigated and leads the annual updates of the 'Global Carbon Budget' bringing together contributions from over 100 scientists worldwide. She was a lead author in several reports of the Intergovernmental Panel on Climate Change (IPCC). She was elected Fellow of the Royal Society in 2016, and received several awards for her work, including the Blaise Pascal Medal of the European Academy of Sciences (2015) and the Grande Médaille Albert 1er de Monaco (2015). She conducts research on the interactions between climate change and the carbon cycle. She was the first to identify a potential weakening in the Southern Ocean carbon sink using atmospheric observations. She spearheaded the developments of the PlankTOM global biogeochemistry model, which initiated ecosystem modelling based on Plankton Functional Types to study interactions between marine biogeochemical cycles and climate change. She is Director of the Tyndall Centre for Climate Change Research until the end of 2018, when she will return to a Professorial post at UEA.

Dr Andrew C. Manning (M) [4C Task 1.1] is Reader (Associate Professor) in UEA's School of Environmental Sciences and leads UEA's Carbon Related Atmospheric Measurement (CRAM) Lab. and Calibration Cylinder Filling Facility. He conducts research primarily on measuring and understanding the atmospheric variations of oxygen, which are driven by the same processes as variations in CO_2. He developed the world's first continuous, high precision atmospheric O_2 analyser in the last 1990s, and he has led European and global atmospheric measurement intercomparison programmes for more than a decade. Dr Manning also has expertise in the measurement and analysis of a range of greenhouse gases and related atmospheric trace gases. He was contributing author in two IPCC Reports.

Dr Anthony De-Gol (M) [4C Task 4.1] is Senior Research Associate in the Tyndall Centre, with expertise in computational physics. He has over 14 years of experience in computational modelling and the development of web-mobile applications to support research. He has developed the ScienceBrief web application that will be used to support 4C research.

Dr Penelope Pickers (F) [4C Task 1.1] is Senior Research Associate in the Tyndall Centre with six years of experience in high precision atmospheric CO_2 and O_2 measurement and data analysis including shipboard atmospheric measurements.

Ms Rebecca Wright (F) [4C Task 1.1] is completing a PhD on global ocean biogeochemistry modelling at UEA (with Le Quéré). She has 3 years of experience working with the NEMO-PlankTOM model that will be used in 4C.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. **Le Quéré, C.,** Andrew, R.M**., Friedlingstein, P., Sitch, S.,** J. Pongratz, **Manning A.C.** et al. (2018), Global Carbon Budget 2017, Earth System Science Data, vol. 10, no. 1, pp. 405-448.
2. Peters, G. P., **Le Quéré, C.,** Andrew, R. M., Canadell, J. G., Friedlingstein, P., Ilyina, T., Jackson, R. B., Joos, F., Korsbakken, J. I., McKinley, G. A., Sitch, S., and Tans, P. (2017). Towards real-time verification of CO_2 emissions, Nature Climate Change, 7, 848-850.

3. **Pickers, P. A., Manning**, A. C., Sturges, W. T., **Le Quéré, C.**, Fletcher, S. E. M., Wilson, P. A., and Etchells, A. J. (2017). In situ measurements of atmospheric O_2 and CO_2 reveal an unexpected O_2 signal over the tropical Atlantic Ocean, Glob. Biogeochem. Cycle, 31, 1289-130.
4. **Le Quéré, C.**, E. T. Buitenhuis, R. Moriarty, S. Alvain, O. Aumont, L. Bopp, S. Chollet, C. Enright, D. J. Franklin, R. J. Geider, S. P. Harrison, A. Hirst, S. Larsen, L. Legendre, T. Platt, I. C. Prentice, R. B. Rivkin, S. Sathyendranath, N. Stephens, M. Vogt, S. Sailley, and S. M. Vallina (2016). Role of zooplankton dynamics for Southern Ocean biomass and global biogeochemical cycles. *Biogeosciences*, **13,** 4111-4133.
5. Shilong Piao, Mengtian Huang, Zhuo Liu, Xuhui Wang, **Philippe Ciais**, **Josep G. Canadell**, Kai Wang, Ana Bastos, **Pierre Friedlingstein**, Richard A. Houghton, **Corinne Le Quéré**, Yongwen Liu, Ranga B. Myneni, Shushi Peng, Julia Pongratz, **Stephen Sitch**, Tao Yan, Yilong Wang, Zaichun Zhu, Donghai Wu and Tao Wang (2018). Lower land-use emissions responsible for increased net land carbon sink during the slow warming period. *Nature Geoscience*, https://doi.org/10.1038/s41561-018-0204-7 .

5 relevant previous projects or activities, connected to the subject of this proposal

1. Annual update of the Global Carbon Budget by the Global Carbon Project (UEA lead, with Exeter and CICERO)
2. EMBRACE - Earth system Model Bias Reduction and assessing Abrupt Climate change – H2020 project, 2011-2015.
3. VERIFY – Observation-based system for monitoring and verification of greenhouse gases – H2020 project, 2017 - 2021
4. SONATA - Southern OceaN optimal Approach To Assess the carbon state, variability and climatic drivers – UK Natural Environment Research Council (NERC), 2017-2021
5. OXYFLUX - Oxygen flux measurements as a new tracer for the carbon and nitrogen cycles in terrestrial ecosystems – ERC Götingen-led project 2016-2021 with Manning and Pickers involved

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

UEA developed the innovative web platform ScienceBrief.org, with funding from the UK NERC. ScienceBrief helps scientists to select new scientific evidence and incorporate it into existing scientific assessments. The IT infrastructure is in place and will be available for use by 4C.

Partner name: Ecole Normale Supérieure (ENS)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

Ecole normale supérieure: Both a French grande école and a university, the Ecole normale supérieure (www.ens.fr) provides in Paris, at the heart of the Quartier latin, excellent training through research, leading to various teaching and research professions, and contributes to train through research the senior executives of public administrations as well as of French and European companies. The ENS also defines and applies scientific and technological research policies, from a multidisciplinary and international perspective. Intellectual freedom, multidisciplinarity in humanities and sciences, individual attention to students, bountiful campus life, gathering students and professors from all disciplines, form the heart of the specificities of the Ecole normale supérieure. Since more than 2 centuries, the ENS prepares its students to the most various openings and the highest responsibilities, while being fully invested in the intellectual, scientific and cultural debates of its time – in particular through the multiplicity of the normaliens' engagement. The École normale supérieure welcomes in its 15 departments for training and research, 800 researchers and teacher researchers, 300 post-doctoral researchers and 600 doctoral students.

Within the department of Geosciences at the Ecole normale supérieure, the Laboratoire de Météorologie Dynamique at ENS (LMD-ENS) hosts ~50 researchers, post-doctoral researchers and doctoral students. It is member of the *Institute Pierre-Simon Laplace* (IPSL) that federates six large research centres, all localised in Paris and around, and studying environmental sciences. Its main objectives are to understand the evolution of the Earth's climate as well as the dynamical processes driving the fluid envelops at the Earth surface. The research of LMD-ENS is clearly positioned at the same time on fundamental research on physical, chemical and biogeochemical processes, the dynamics and the physics of the atmosphere, ocean and the climate, and on finalized research, around particular questions relating to the anticipation of the global warming and its consequences. These scientific objectives are striven forward by the complementary approaches that goes from theory, observing, and modeling.

Role in the project: LMD-ENS will contribute to all WPs with enhanced contributions to WP2 and WP3. In WP2, LMD-ENS will focus on delivering and analysing decadal simulations performed with the IPSL Earth System Model (IPSL-ESM), specifically designed to study the predictability of the global carbon cycle. In WP3, LMD-ENS will focus on climate-carbon feedbacks and will develop new methods to constrain the evolution of the ocean carbon uptake in the coming decades and centuries.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Dr. Laurent Bopp (M) [4C Task 2.4 lead] is a Senior Research Scientist at the Centre National de la Recherche Scientifique (CNRS) and adjunct Professor at the Ecole normale supérieure (ENS). He conducts his research at the Laboratoire de Météorologie Dynamique, which is part of the Institut Pierre Simon Laplace (IPSL). His main research interests concern the links between climate change, marine biogeochemistry and ocean ecosystems. He is an expert in ocean biogeochemistry modeling and has been among the first to introduce marine biogeochemistry in climate models to study carbon-climate feedbacks and the impact of climate change on marine ecosystems. He was involved in the last IPCC report as a lead author; he is a member of the Scientific Steering Committee of IMBeR (Integrated Marine Biosphere Research) since 2014; he is also involved in the EU H-2020 CRESCENDO project (WP leader) on the next generation of Earth System models.

Dr Juliette Mignot (F) [4C WP2] is a researcher at the Institut pour la Recherche et le Développement (IRD) and conducts her research at LOCEAN / IPSL. She is specialized in physical oceanography and climate variability. Her objectives are to better understand the climate low frequency variability and in particular the role of the ocean and of external forcings. She has worked on the decadal climate variability of the Atlantic, on decadal prediction and predictability assessment, on understanding and characterizing the role of salinity in the oceanic stratification. She uses several statistical tools and climate models. She has been one of the initiators of the decadal predictability activities at IPSL/LOCEAN. She is also a member of the steering committee of the IPSL modelling group.

Dr. Patricia Cadule (F) [4C WP3] currently works at the Centre National de la Recherche Scientifique (CNRS) at which she leads the technical development of the next generation climate carbon coupled models (IPSL Earth System Model). Her research interests cover the modelling of carbon and nitrogen cycles, the benchmarking of biogeochemical models, the definition of emerging constraints, and the climate-carbon future interactions. She is involved in international (e.g, Coupled Model Intercomparison Project CMIP Phase 6) and European (e.g., CRESCENDO, ESA CMUG) projects, and leads the national (MGClimDeX) collaborative project addressing climate change and its impact on society in the Caribbean region.

LMD-ENS will contribute to all WPs with enhanced contributions to WP2 and WP3. In WP1, LMD-ENS will focus on delivering and analysing simulations performed with the IPSL Earth System Model (IPSL-ESM), specifically designed to study the predictability of the global carbon cycle. In WP3, LMD-ENS will focus on climate-carbon feedbacks and will develop new methods to constrain the evolution of the ocean carbon uptake in the coming decades and centuries.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. Kwiatkowski, L., Bopp, L., Aumont, A., Ciais, P., Cox, P.M., Laufkötter, C., Yue, L., Séférian, R. Emergent constraints on projections of declining primary production in the tropical oceans. *Nature Climate Change*, doi: 10.1038/nclimate3265, 2017.

2. Bopp, L., Lévy, M., Resplandy, L., and Sallée, J.B, Pathways of anthropogenic carbon subduction in the global ocean. Geophysical Research Letters *42*, doi:10.1002/2015GL065073, 2015.
3. Seferian, R., Bopp, L., Gehlen, M., Swingedouw, D., Mignot, J., Guilyardi, E., and Servonnat, J. (2014). Multiyear predictability of tropical marine productivity. Proceedings of the National Academy of Sciences *111*, 11646–11651.
4. Mignot, J., García-Serrano, J., Swingedouw, D., Germe, A., Nguyen, S., Ortega, P., Guilyardi, E., and Ray, S. (2016). Decadal prediction skill in the ocean with surface nudging in the IPSL-CM5A-LR climate model. Clim Dyn *47*, 1225–1246.
5. Cadule, P., Friedlingstein, P., Bopp, L., Sitch, S., Jones, C.D., Ciais, P., Piao, S.L., and Peylin, P. (2010). Benchmarking coupled climate-carbon models against long-term atmospheric CO_2 measurements: Global Biogeochemical Cycles *24*, n/a-n/a.

5 relevant previous projects or activities, connected to the subject of this proposal

1. CRESCENDO (641816): This H2020 project facilitates a coordinated European contribution to the **6th Coupled Model Intercomparison Project** (CMIP6) where the climate research community compares a range of International Earth System Models using common sets of experimental protocols, to improve our knowledge of the Earth's climate processes and provide the best possible future projections to governments and decision-makers. CRESCENDO in particular better informs a number of key Model Intercomparison Projects (MIPs) where biogeochemical and aerosol components are of critical importance to delivering realistic future projections. Such components include: the terrestrial and marine carbon cycle, vegetation processes, permafrost, atmospheric chemistry and aerosols.
2. EUCP (European Climate Prediction System Project, 776613) : This H2020 project has the following four objectives: 1. Develop an innovative ensemble climate prediction system based on high-resolution climate models for Europe for the near-term; 2. Use the climate prediction system to produce consistent, authoritative and actionable climate information; 3. Demonstrate the value of this climate prediction system through high impact extreme weather events in the near past and near future; 4. Develop, and publish, methodologies, good practice and guidance for producing and using authoritative climate predictions for the 1-40 year timescale.

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

N/A

Partner name: Max-Planck-Gesellschaft zur Förderung der Wissenschaft e.V. (MPG), represented by the Max-Planck-Institutes for Meteorology (MPI-M) and Biogeochemistry (MPI-BGC)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The **Max Planck Society (MPG)** is Germany's most successful research organization established in 1948. Max Planck Institutes focus on research fields that are particularly innovative, or that are especially demanding in terms of funding or time requirements. The MPG contributes to the project with two of its institutes:

Max Planck Institute for Meteorology (MPI-M)

MPI-M (http://www.mpimet.mpg.de) is dedicated to fundamental climate research. The overall mission of MPI-M is to understand how chemical, physical, and biological processes, as well as human behavior contribute to the dynamics of the Earth system, and specifically how they relate to global climate changes. MPI-M develops a state-of-the-art MPI Earth System Model (MPI-ESM), which includes components dealing with the atmosphere (ECHAM), ocean and sea ice (MPIOM), land surface & biosphere (JSBACH), and oceanic biogeochemistry processes (HAMOCC). MPI-M acts as the focal point of climate research in Germany since 30 years, also contributing to integrated assessment studies and socio-economic/climate interactions. MPI-M is committed to make MPI-ESM available to the scientific community in Europe and elsewhere and to inform decision-makers and the public on questions related to Climate Change and Global Change. MPI-M manages an International Max Planck Research School (IMPRS) for Earth System Modeling, which hosts approximately 50 PhD students.

MPI-M develops MPI-ESM and uses it to understand and project climate and carbon cycle dynamics, in particular under anthropogenic forcings. The MPI-ESM is used in the sixth phase of the coupled model intercomparison project (CMIP6) in concerted action with many other world leading climate centres, including groups developing other European ESMs (e.g., EC-Earth, IPSL-CM, UKESM). A strength of the MPI-M team is in joint efforts of land, ocean, and atmospheric departments on linking processes and feedbacks in the Earth System.

Max Planck Institute for Biogeochemistry (MPI-BGC)

The MaxPlanck-Institute for Biogeochemistry (MPI-BGC) belongs to the key research institutes worldwide in biogeochemical Earth system science. Its research mission is the investigation of global biogeochemical cycles and their interaction with the climate system. The institute combines strong observational expertise (in-situ and remote sensing greenhouse gas observations, vegetation-atmosphere fluxes, etc.) with local to global scale biosphere and atmosphere modelling (e.g. carbon cycle). Currently the institute has a total staff of about 230 from more than 25 different countries. In cooperation with the local university, it manages the International Max Planck Research School (IMPRS) for global Biogeochemical Cycles, hosting almost 60 PhD students.

Role in the project: MPG will co-lead WP2 and contribute to all WPs. In WP1, MPG will lead T1.2 on development of new data-based products for global carbon evaluation. MPG will perform and evaluate historical simulations with the MPI-ESM and its offline land and ocean components, also contributing to the attribution analysis. With the MPI-ESM, MPG will perform the simulations and analyse the decadal prediction of the carbon cycle in WP2, and contribute to the work on adaptive scenarios in WP3. MPG will contribute to WP4 on synthesis and dissemination, supporting the IPCC assessment.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Prof Victor Brovkin (M) [4C WP1&3] leads a scientific group on Climate-Biogeosphere Interactions in the Land in the Earth System Department at MPI-M. His research is focused on analysis of biogeophysical and biogeochemical feedbacks between vegetation, carbon cycle, and climate using Earth System models. He contributes as an Editor to the carbon cycle chapter of the IPCC WGI Assessment Report 6. His group is actively involved into development of the MPI-ESM land surface model, JSBACH, with a main contribution to modelling of long-term processes (vegetation and soil carbon dynamics, permafrost).

Dr Tatiana Ilyina (F) [4C WP2 co-lead] is head of the Ocean Biogeochemistry group within the Ocean in the Earth System Department at MPI-M and co-chairs the World Climate Research Program's Grand Challenge on Carbon Feedbacks in the Climate System together with Prof. Friedlingstein. Her research interests span the areas of uptake and storage of carbon by the ocean and their variability, carbon-climate feedbacks, ocean acidification, evolution of the oxygen minimum zones in past, present, and future climates. Her recent research focus has been on understanding the origins of variability and predictability of the ocean carbon sink with the aim of improving predictive skill of climate-carbon cycle models.

Dr. Peter Landschützer (M) [4C Task 1.2 lead] Dr. Landschützer is an expert in the ocean carbon cycle, in particular in analysing observations of the surface ocean partial pressure of carbon dioxide (pCO_2) and the resulting air-sea exchange of CO_2 between the ocean and the atmospheres. His combined knowledge of ocean observations, big data mining, machine learning and numerical modelling led to the discovery that the ocean carbon sink is more variable on decadal timescales than previously recognised mainly by model studies. The observation-based pCO_2 and air-sea CO_2 flux fields of Dr. Landschützer are used by several groups, e.g. by the Global Carbon Project for the annual Global Carbon Budget.

Dr. Sönke Zaehle (M) [4C WP1&3] is an expert in land surface and land biogeochemical model, in particular in the interactions of the terrestrial nitrogen and phosphorus cycles with the carbon cycle, and has significantly contributed to the understanding of the relevance of nitrogen effects on global land-climate feedbacks. His expertise ranges from the development of novel process formulation, the systematic testing of models with various data streams from ecological montioring and manipulation to atmospheric inversions and remotely sensed data. He is actively contributing to the Global Carbon Project's annual Global Carbon Budget.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. **Brovkin, V.,** Boysen, L., Arora, V., Boisier, J., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., van den Hurk, B., Hurtt, G., Jones, C., Kato, E., de Noblet-Ducoudré, N., Pacifico, F., Pongratz, J. & Weiss, M. (2013) Effect of anthropogenic land-use and land cover changes on climate and land carbon storage in CMIP5 projections for the 21st century. Journal of Climate, 26, 6859-6881.
2. Li H., **Ilyina T**., Müller W.A., Sienz F. (2015) Decadal predictions of the North Atlantic CO_2 uptake. Nature Communications, doi: 10.1038/ncomms11076.
3. **Ilyina T.,** Six K.D., Segschneider J., Maier-Reimer E., Li H., Núñez-Riboni I. (2013) The global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth System Model in different CMIP5 experimental realizations. J. Adv. Model. Earth Syst., 5(2): 287-315.
4. **Landschützer, P.,** Gruber, N., Haumann, F. A. Rödenbeck, C. Bakker, D. C. E., van Heuven, S. Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., Tilbrook, B. and Wanninkhof, R. (2015) The reinvigoration of the Southern Ocean carbon sink, Science, 349, 1221-1224.
5. **Zaehle S.,** Jones C.D., Houlton B., Lamarque J.-F., Robertson E. (2015) Nitrogen Availability Reduces CMIP5 Projections of Twenty-First-Century Land Carbon Uptake. *Journal of Climate*. 28(6):2494–2511. doi:10.1175/JCLI-D-13-00776.1.

5 relevant previous projects or activities, connected to the subject of this proposal

1. H2020 project CRESCENDO (Improvement of Earth System Models)
2. Marie Curie ITN C-CASCADES (Carbon Cascades from Land to Ocean)
3. German BMBF project MiKlip (Decadal predictions)
4. Marie Curie ITN GREENCYCLES II (Global Biospheric Feedbacks)
5. ERC consolidator grant QUINCY (Global Nutrient Carbon-Cycle interactions and climate feedbacks)

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

MPI-M: To satisfy the extensive computational needs of the MPI-M and MPI-BGC, the institutes built strategic partnership with the German Climate Computing Centre (DKRZ), the German collaborator of the Earth System Grid Federation (ESGF). The MPI-M has for a long time benefited from a close integration of its systems with those of DKRZ, offering the MPI-M seamless access to the DKRZ-managed machines such as Bull machine "mistral", the supercomputer with a peak performance of 3.14 Petaflops consisting of approx. 3,000 compute nodes, 100,000 compute cores, 240 Terabytes of memory, and 54 Petabytes of disk. "Mistral" is used for CMIP6 simulations.

MPI-BGC departments share a number of excellent central facilities (e.g. laboratory analyses including state-of-the-art isotope work, central IT services, etc.) providing outstanding assistance for conducting research projects. All central service groups are integral parts of MPI-BGC, located in-house and dedicated almost exclusively to support MPI-BGC research. In terms of computational resources for modeling activities, the MPI-BGC hosts a high-performance computing cluster (with over 1500 CPU's of 2.3GHz) that are regularly upgraded, and also provides access to state-of-the-art supercomputers hosted by the German Climate Computing Center (DKRZ) in Hamburg.

Partner name: ETH Zurich

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal
The Swiss Federal Institute of Technology (ETH) was founded in 1855 and is the leading Swiss university in the areas of natural sciences and engineering, with about 20,000 students and 6000 staff. Currently, it is ranked 7th worldwide according to the 2018 QS world university ranking. Moreover, according to the Nature Index 2018, ETHZ is the world's top ranked university in the field of Earth and Environmental Sciences. The Institute of Atmospheric and Climate Science (IAC) at ETH Zurich has long and wide-ranging expertise in atmospheric physics, climate research, hydrometeorology and biosphere-climate interactions. IAC includes seven professorships and a staff of about 130 researchers, technicians and Ph.D. students. The Institute for Biogeochemistry and Pollutant Dynamics (IBP) encompasses eight professorships and nine associated research groups. With approximately 100 PhD students and 20-30 postdocs, IBP works in a highly interdisciplinary manner on the advancement of the understanding of natural biogeochemical cycles and processes in natural and man-made environments and potential responses to human activity and global change. **Role in the project:** ETHZ will mainly be involved in WP1 and WP3, leading Tasks 1.3 and 3.1. In WP1, ETHZ will be contributing to the development of new observational constraints for the ocean interior and for the land water cycle. ETHZ will perform, and evaluate historical simulations of the ocean carbon cycle, also contributing to the attribution analysis. In WP3, ETHZ will lead the task T3.1 on development of new emergent constraints, and contribute to the assessment of TCRE and future projections.
Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities
Sonia Seneviratne (F) [4C Task 3.1 lead], professor and chair of the Land-Climate Dynamics research group, is an expert in land-atmosphere and biosphere-climate interactions, extremes research, land water control on plants and land carbon exchange, land water observations, low-emissions scenarios, and land surface and climate modelling. She is currently a Coordinating Lead Author of the IPCC 6th assessment report and a Lead Author of the IPCC Special Report on 1.5°C global warming. She is also a co-chair of the World Climate Research Program (WCRP)'s Grand Challenge on Extremes, and from 2014 to 2018, she was the co-chair of WCRP's Global Energy and Water Cycle Exchange project (GEWEX). She has published more than 150 scientific articles, of which more than 20 in high-impact journals. Since 2014 she has been listed as highly cited researcher by Thomson Reuters and Clarivate Analytics. In 2014, she received the *Macelwane medal of the American Geophysical Union*, and was elected AGU fellow. **Nicolas Gruber (M)** [4C Task 1.3 lead] professor and chair of the Environmental Physics research group, is an expert on the global cycles of carbon and other biologically essential elements and their interaction with the climate system. He combines the analysis of observations with modelling studies to better quantify, for example, the role of the ocean in the global carbon cycle. He is currently a lead author for the IPCC Special Report on the Ocean and Cryosphere, and chaired the international joint IMBER/SOLAS working group on ocean carbon between 2008 and 2016. He has authored or co-authored more than 160 publications, including 20 in the top impact journals. Further, he wrote together with Jorge Sarmiento the textbook "Ocean Biogeochemical Dynamics" that has become a standard text in the field. In recognition of his outstanding contribution to Marine Sciences, Dr. Gruber received the *Rosenstiel Award* from the University of Miami in 2004. In 2012 he was elected *fellow of the American Geophysical Union*. He is member of several international research boards and serves as review editor for the *Science* Magazine. **Edouard Davin (M)** [4C WP1&3] is senior scientist in the Land-Climate Dynamics group. He investigates the role of the terrestrial biosphere in the climate system, including the terrestrial carbon cycle, with a focus on human-induced land cover changes and land management impacts. He has expertise is in using complex coupled climate models and improving the representation of land processes in these models. He is currently a Lead Author of the IPCC Special Report on Climate Change and Land.

Vincent Humphrey (M) [4C WP1&3] is a postdoctoral researcher in the Land-Climate Dynamics group. He has expertise in satellite measurements of the land water cycle, statistical reconstructions of land water datasets, as well as in carbon-water interactions on land.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. **Humphrey, V**., J. Zscheischler, P. Ciais, L. Gudmundsson, S. Sitch, and **S.I. Seneviratne**, 2018: Sensitivity of atmospheric CO_2 growth rate to observed changes in terrestrial water storage. *Nature*.
2. Mystakidis, S., **S.I. Seneviratne**, **N. Gruber**, and **E.L. Davin**, 2017: Hydrological and biogeochemical constraints on terrestrial carbon cycle feedbacks. *Environmental Res. Lett*., 12, 014009
3. **Seneviratne, S.I.**, J. Rogelj, R. Séférian, R. Wartenburger, M.R. Allen, M. Cain, R.J. Millar, K.L. Ebi, N. Ellis, O. Hoegh-Guldberg, A.J. Payne, C.-F. Schleussner, P. Tschakert, R.F. Warren, 2018: The many possible climates from the Paris Agreement's aim of 1.5°C warming. *Nature*. 558, 41-49.
4. Landschützer, P., **N. Gruber**, et al., The reinvigoration of the Southern Ocean carbon sink, *Science*, 349(6253), 1221-1224, doi:10.1126/science.aab2620, 2015.
5. **Gruber, N.**, P. Landschützer, and N. Lovenduski, The variable Southern Ocean carbon sink, *Annu. Rev. Mar. Sci.*, 11, doi: 10.1146/annurev-marine-121916-063407, 2019.

5 relevant previous projects or activities, connected to the subject of this proposal

1. European Research Council (ERC) Consolidator Grant "DROUGHT-HEAT", 2014-2019 [S.I. Seneviratne]
2. H2020 CRESCENDO Project, 2015-2020 [S.I. Seneviratne, E.L. Davin]
3. Coordinating Lead Author of IPCC 6th Assessment Report (Extremes chapter) [S.I. Seneviratne], Lead Author of IPCC Special Report on Climate Change and Land [E.L. Davin], Lead Author of IPCC Special report on Ocean and Cryosphere [N. Gruber]
4. FP 7 Carbones, FP7 EPOCA, FP 7 ITN Marie Curie Greencycles II [N. Gruber: Participant]
5. FP 7 CarboChange: [N. Gruber Core Theme leader], FP 7 GeoCarbon [N. Gruber, Component leader], FP 8 ITN Marie Curie C-Cascades: [N. Gruber: Executive Team]

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

Collection of land water cycle and ocean datasets in the Land-Climate Dynamics and the Environmental Physics groups (>120 Terabytes), including a reconstruction of land water storage over the time period 1900-2018 and a reconstruction of the ocean carbon sink 1980-2017.

Partner name: Barcelona Supercomputing Center – Centro Nacional de Supercomputación (BSC)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The **Barcelona Supercomputing Center-Centro Nacional de Supercomputación** (**BSC**, https://www.bsc.es) combines unique high performance computing facilities and in-house top research departments on Computer, Life, and Earth sciences, and in computational applications in science and engineering. It is the main provider of public supercomputing services in Spain, coordinating the Red Española de Supercomputación and representing Spain in international initiatives such as PRACE (http://www.prace-ri.eu/). The **Earth Sciences (ES) Department** focuses on the atmosphere-ocean-biosphere system and is structured around four groups with more than 70 researchers and support staff. It is a highly productive scientific entity that has published more than 160 research peer-reviewed articles over the last 5 years, many in high-impact journals.

Within the ES Department, the **Climate Prediction Group (CPG)** aims at developing a climate forecast system based on the Earth System Model EC-Earth. The CPG also performs regular assessments of the system's predictive capacity and compares it with other operational and quasi-operational systems in the world. The CPG has a long experience in seasonal to decadal climate prediction, which has been reflected in its active participation to several European projects with a strong component on climate prediction (see list below). Of particular relevance was the FP7 project SPECS, led by the BSC, in which specific, innovative global forecast system experiments were coordinated to test hypotheses for the improvement of seasonal to decadal predictions. The CPG currently participates to 10 European and 4 national projects. The group has been expanding its research activities on prediction, and is contributing to the development of the CMIP6 version of EC-Earth, which will be available by the end of the summer of 2018. With the final model version, the group will strongly contribute to DCPP (Decadal Climate Prediction Project), and C4MIP (Coupled Climate-Carbon Cycle Model Intercomparison Project). In addition, members of the group are currently testing several techniques to produce optimal initial conditions for decadal predictions of climate and global carbon cycle. Results from this effort will be paramount for the work proposed in WP2 that will be co-led by Dr. Raffaele Bernardello.

Also within the ES Department, the **Earth System Services** group **(ESS)** aims at demonstrating the ongoing value of climate prediction services, atmospheric composition and weather forecasting to society and the economy. The group actively works in identifying user needs that will partly guide research in the BSC-ES Department and aims to quantify the impact of weather, climate, aerosols and gaseous pollutants upon socio-economic sectors through the development of user-oriented services that ensure the transfer of the technology developed and the adaptation to a rapidly changing environment, especially of those highly vulnerable. This group is coordinating the H2020 project S2S4E-776787 "Subseasonal to seasonal climate predictions for energy" and has a key role in other European and national projects on climate services such as ClimatEurope-689029, MEDGOLD-776467, VISCA-730253 and EUCP-776613. The ESS has an interdisciplinary approach closely collaborating with research groups and general support groups at the BSC (technology transfer, communications, visualisation, education and outreach). This multidisciplinary expertise will be used in WP4, co-led by Dr. Isadora Jiménez, to effectively translate the scientific outcomes of 4C into actionable information for the target users.

Role in the project: BSC will co-lead WP2, developing, performing and analysing decadal prediction of the carbon cycle with the EC-Earth-ESM. BSC will also co-lead WP4 on synthesis, dissemination, and policy dialogue. BSC will also use to EC-Earth-ESM to contribute to the historical simulations in WP1 and adaptive scenarios in WP3.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Dr. Raffaele Bernardello (M) [4C WP2 lead] has a PhD in Oceanography from the Universitat Politecnica de Catalunya-BarcelonaTech. He is a senior researcher in the climate prediction group at BSC where he coordinates all the activities related to the global carbon cycle. He will be the principal investigator for BSC in 4C and co-leader of WP2. His expertise and research interests are in the broad context of the interactions between climate dynamics and global carbon cycle. As part of his Marie-Curie fellowship, Dr. Bernardello worked on the assessment of the decadal predictability of biogeochemical properties in the upwelling systems of the Atlantic Ocean. He has participated to 3 national projects (Spain: OAMMS-CTM2008-03983 UK: BATMAN-NE/K015613/1 USA: NOAA-NA10OAR4320092), one FP6 project (SESAME-36949) and one ESA project (ENVISAT-A0290). At present, Dr. Bernardello supervises one postdoctoral researcher and he is the PI of a Spanish project (DeCUSO-CGL2017-84493-R) dedicated at investigating the decadal predictability of carbon uptake in the Southern Ocean, serving at the same time, as an external collaborator in the UK project CUSTARD with focus on Southern Ocean biogeochemical processes.

Dr. Isadora Jimenez (F) [4C WP4 lead] has a Master's degree in Science communication (IDECUPF) and a PhD in Biology from the University of Barcelona. She has eight years of research experience in direct contact with renewable energy stakeholders and seven years working on science communication. As senior science communication specialist of the Earth System Services group at BSC-ES she coordinates a multidisciplinary team of five people that facilitates knowledge and technology transfer to end users including industry (e.g. renewable energy, agriculture) and policy makers. In 4C she will co-lead WP4 using her expertise to maximise the impact of the project through dissemination and stakeholders engagement. She is currently involved in EU funded projects in dissemination actions, user engagement activities and the interaction with stakeholders to promote the integration of climate predictions in decision making processes. She is part of the coordination team of S2S4E-776787. She was key role of FP7 project EUPORIAS-308291, and Work Package leader within FP7 and H2020 projects EUPORIAS-308291, PRIMAVERA-641727 and APPLICATE-727862. Her team contributes to dissemination and user engagement activities of SPECS-308378, IMPREX-641811, Climateurope-689029, MED-GOLD-776467 and EUCP-776613 projects.

Dr. Etienne Tourigny (M) [4C WP1&2] has a PhD in Meteorology from the Instituto Nacional de Pesquisas Espaciais (INPE-CPTEC, Brasil) and a M.Sc. in Atmospheric Science from the Université du Québec à Montréal (UQAM). Dr. Tourigny has a strong multi-disciplinary background, having studied physics, computer science, atmospheric science and biosphere-atmosphere interactions. He has professional experience in the Information Technology sector, before transitioning to the climate research field where he developed his expertise in the field of climate seasonal prediction, having studied the impacts of ENSO on precipitation anomalies in the tropical Americas. He contributed to the development of the Brazilian Earth System Model (BESM) at INPE – CCST acquiring in the process a very strong expertise in vegetation and fire modelling as well as in high-performance computing. After obtaining a Marie-Curie fellowship, Dr. Tourigny joined the climate prediction group at BSC where he is developing a new research line on seasonal predictions of wildfires while, at the same time, actively contributing to the development of the CMIP6 version of the EC-Earth ESM.

Prof. Francisco J. Doblas-Reyes (M) [4C WP2] is the **Director of the Earth Science Department at BSC**. Prof. Doblas-Reyes has more than 20 years of experience in weather and climate modelling, climate prediction, as well as in the development of climate services. He has worked at several internationally-recognized institutions like INTA (Spain), CNRM (France), ECMWF (UK) and IC3 (Spain). At ECMWF, he worked on seasonal climate forecasting in two ground-breaking European projects: FP5 DEMETER (00024) and FP6 ENSEMBLES (505539). For his work in seasonal forecasting Prof Doblas-Reyes was awarded the Norbert Gerbier-MUMM International Award from the UN World Meteorological Organization (WMO) in 2006. He serves in several panels of the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP); he is a lead author of the IPCC and a member of the European Network for Earth System modelling HPC Task Force. Moreover, Prof, Doblas-Reyes has either led or participated in numerous national and European FP4, FP5, FP6 and FP7 projects, including the coordination of FP7 project SPECS (308378). Currently, Prof. Doblas-Reyes is the principal investigator or co-investigator in 5 H2020 European projects (including PRIMAVERA-641727), 1 national project (CLINSA-CGL2017-85791-R) and he is leading a COPERNICUS action (QA4SEAS). At the same time, he supervises numerous postdoctoral scientists and software engineers and has obtained 50 Million hours of computing time for the High Resolution Ensemble Climate Modeling project through the PRACE network. Overall, Prof. Doblas-Reyes has authored and co-authored more than 100 peer-reviewed papers on climate modeling and prediction, as well as climate services, and currently has a total of 6103 citations with a h-index of 39.

Ilaria Vigo (F) [4C WP4] holds a Master's Degree in Economics from Barcelona Graduate School of Economics and a Bachelor's Degree in Economics from University of Pavia. She devoted part of her studies to the research on Environmental Economics. Ilaria has experience as Policy Adviser consulting in European Commission funded projects, for Governments and for private sector as well. Additionally, she worked as Research Assistant in Economics at Pompeu Fabra University. In order to generate a social impact, Ilaria believes in the importance of communication and stakeholder engagement. She has experience in event management and communication activities. Finally, Ilaria is native Italian, fluent in English and Spanish, and intermediate in Portuguese.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. Volpi, D., V. Guemas, F.J. Doblas-Reyes, E. Hawkins and N. Nichols (2017). Decadal climate prediction with a refined anomaly initialisation approach. *Clim. Dyn. 48, 1841-1853*.

2. Volpi D., V. Guemas and F.J. Doblas-Reyes (2017). Comparison of full field and anomaly initialisation for decadal climate prediction: towards an optimal consistency between the ocean and sea-ice anomaly initialisation state. *Clim. Dyn.* 49, 1181-1195.
3. Bernardello R., I. Marinov, J.B. Palter, E. Galbraith, J.L. Sarmiento and R. Slater (2014). Response of the Ocean Natural Carbon Storage to Projected Twenty-First-Century Climate Change, *Journal of Clim.* 27, 2033-2053.
4. Guemas V., F.J. Doblas-Reyes, I. Andreu-Burillo and M. Asif (2013). Retrospective prediction of the global warming slowdown in the past decade. *Nat. Clim. Change* 3, 649-653.
5. Doblas-Reyes, F.J., I. Andreu-Burillo, Y. Chikamoto, J. García-Serrano, V. Guemas, M. Kimoto, T. Mochizuki, L.R.L. Rodrigues and G.J. van Oldenborgh (2013). Initialized near-term regional climate change prediction. *Nat. Comm.* 4, doi:10.1038/ncomms2704.

5 relevant previous projects or activities, connected to the subject of this proposal

1. DeCUSO (MINECO-Retos-CGL2017-84493-R) Decadal predictions of Carbon Uptake in the Southern Ocean and impact of the biological carbon pump uncertainty.
2. PREFACE (FP7-ENV-2013-603521) https://preface.w.uib.no/. Enhanced prediction of tropical Atlantic climate and its impacts.
3. APPLICATE (H2020-BG-2016-2017-727862) https://applicate.eu/. Advanced Prediction in Polar regions and beyond: Modelling, observing system design and linkages associated with a changing Arctic climate.
4. PRIMAVERA (H2020 SC5-01-2014-641727) https://www.primavera-h2020.eu/. PRocess-based climate sIMulation: AdVances in high-resolution modelling and European climate Risk Assessment
5. EUCP (H2020-SC5-2016-2017-776613) https://www.eucp-project.eu/. European climate prediction system.

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

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 latest version, MareNostrum 4 (since July 2017) 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 like FPGA boards, small clusters based on ARM SoCs, GPUs, etc.

Partner name: Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal
DLR is the German national research establishment for aeronautics, astronautics, and energy technology within the Helmholtz-Gemeinschaft der Forschungszentren (HGF). In 4C, DLR is represented by the Institute of Atmospheric Physics (DLR-IPA). DLR-IPA has long-term experience in several research areas that are of relevance for 4C, in particular global Earth system modelling and evaluation, the analysis of multi-model climate projections, and processing and analysis of satellite data. DLR-IPA is the PI of the Earth System Model Evaluation Tool (ESMValTool, http://www.esmvaltool.org/) that is developed in collaboration with other partners. **Role in the project:** DLR will co-lead WP3. DLR will contribute to WP1 by developing diagnostics to include 4C observations from Task 1.1 and 1.2 into the ESMValTool. In WP3, DLR will develop multi-variate emergent constraints for carbon and biogeochemical feedbacks, provide constraints and a reassessment of TCRE and will provide observationally constrained estimates of CO_2 projections. DLR will contribute to WP4 on synthesis and dissemination, supporting the IPCC assessment
Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities
Prof Dr Veronika Eyring (**F**) [4C WP3 co-lead] is Head of the Earth system model evaluation and –analysis department at DLR-IPA. She is Professor of Climate Modelling at the University of Bremen and maintains a strong collaboration with the National Center for Atmospheric Research (NCAR, USA) as Affiliate Scientist. Her research focuses on Earth system modeling and evaluation with observations. She has authored many peer-reviewed journal articles and has contributed to the Intergovernmental Panel on Climate Change (IPCC) climate and World Meteorological Organization (WMO) ozone assessments since 2004. Veronika is the PI of the ESMValTool and is involved in the World Climate Research Programme (WCRP) through her roles as Chair of the CMIP Panel and member of the scientific steering committees for the Working Group on Coupled Modeling (WGCM), the WCRP Data Advisory Council's (WDAC) Observations for Model Evaluation Task Team, and the Working Group on Numerical Experimentation (WGNE)/WGCM Climate Model Diagnostics and Metrics Panel. **Dr Axel Lauer** (**M**) [4C WP1&3] is a Research Scientist at DLR-IPA and member of the Earth system model evaluation and –analysis department. Before joining the Earth system model evaluation department at DLR, Axel spent five years as a researcher at the International Pacific Research Center in Honolulu (U.S.) studying clouds, aerosols and their interactions and two years at the Institute for Advanced Sustainability Studies in Potsdam (Germany). His main research interests are aerosols, clouds and cloud-climate feedbacks as well as their interactions. He has a long standing experience in evaluating and analysing climate model results and coordinates the technical ESMValTool development together as core developer. **Dr Sabrina Zechlau** (previously Wenzel) (**F**) [4C WP3] is PostDoc at DLR and Member of the Earth system model evaluation and –analysis department. Her research focuses on the evaluation of the carbon cycle in Earth system models and on constraining multi-model projections with observational data. She has been active ESMValTool developer for several years.
5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content
1. **Eyring, V.**, Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, 2016a. 2. Knutti, R., J. Sedláček, B. M. Sanderson, R. Lorenz, E. Fischer, and **V. Eyring** (2017), A climate model projection weighting scheme accounting for performance and interdependence, Geophys. Res. Lett., 44, doi:10.1002/2016GL072012.

3. Lorenz R., N. Herger, J. Sedlacek, **V. Eyring**, E.M. Fischer, and R. Knutti, Prospects and caveats of weighting climate models for summer maximum temperature projections over North America, Journal of Geophysical Research, 123, doi:10.1029/2017JD027992, 2018.
4. **Wenzel, S.**, Cox, P. M., **Eyring, V.** & Friedlingstein, P. Emergent constraints on climate-carbon cycle feedbacks in the CMIP5 Earth system models. Journal of Geophysical Research: Biogeosciences 119, 2013JG002591, doi:10.1002/2013JG002591 (2014).
5. **Wenzel, S.,** Cox, P. M., **Eyring, V.** & Friedlingstein, P. Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO_2. Nature 538, 499-501, doi:10.1038/nature19772 (2016).

5 relevant previous projects or activities, connected to the subject of this proposal

1. ESMValTool PI (**Eyring, V.,** Righi, M., **Lauer, A**., Evaldsson, M., Wenzel, S., Jones, C., Anav, A., Andrews, O., Cionni, I., Davin, E. L., Deser, C., Ehbrecht, C., Friedlingstein, P., Gleckler, P., Gottschaldt, K. D., Hagemann, S., Juckes, M., Kindermann, S., Krasting, J., Kunert, D., Levine, R., Loew, A., Mäkelä, J., Martin, G., Mason, E., Phillips, A. S., Read, S., Rio, C., Roehrig, R., Senftleben, D., Sterl, A., van Ulft, L. H., Walton, J., Wang, S., and Williams, K. D.: ESMValTool (v1.0) – a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP, Geosci. Model Dev., 9, 1747-1802, 2016)
2. BMBF CMIP6-DICAD (2016-2020), German national project to coordinate and fund CMIP6 activities in Germany, responsible for enhancements of the ESMValTool with additional diagnostics and metrics and for establishing a first version of the ESMValTool coupling to the ESGF infrastructure at DKRZ.
3. Copernicus C3S-MAGIC (2016-2019), C3S - Metrics and Access to Global Indices for Climate Projections, work package leader for the development of performance metrics in the ESMValTool (https://climate.copernicus.eu/development-c3s-software-data-analysis-climate-models).
4. Copernicus C3S-511 (2017-2021), Scientific Quality Assessment and Report for ECVs, responsible for the scientific quality assessment of observations related to cloud properties, aerosol, carbon dioxide, and methane with the ESMValTool.
5. EU H2020 CRESCENDO (2015-2020), Coordinated Research in Earth Systems and Climate: Experiments, kNowledge, Dissemination and Outreach, responsible for the research theme Earth System Model Evaluation (https://www.crescendoproject.eu/).

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

To facilitate the development by multiple users and institutions, the development of the ESMValTool is conducted at GitHub, using an open repository that is available to the public (https://github.com/ESMValGroup/ESMValTool) and a private repository that is restricted to the ESMValTool Development Team. The ESMValTool is based on open-source software, such as Python and the NCAR Command Language (NCL), which are available on most computer facilities, including the DLR-IPA Linux Cluster. DLR-IPA runs global simulations with the EMAC model and the ESMValTool at supercomputing centers such as the German Climate Computing Center (DKRZ, Hamburg) and the Leibniz Supercomputing Center (LRZ, Garching). In addition to these resources, DLR-IPA has also access to a local Linux-cluster.

Partner name: UNIVERSITY OF BREMEN (UBREMEN)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The University of Bremen (UBREMEN) is a young research university and one of the top 50 European universities under the age of 50. Together with the local research institutes and cooperation partners, it belongs to the leading research facilities in northwest Germany with an excellent performance in many areas of national and international research. UBREMEN has selected a set of scientific foci for its international research profile, the first addressing ocean, polar, and climate research. The Institute of Environmental

Physics (IUP) of the University of Bremen addresses this focus directly. It is the leading University research center for atmospheric remote sensing, internationally recognized for its excellence. The IUP is part of the faculty of Physics/Electrical Engineering and has more than 100 employees distributed over six departments.

The department of Physics and Chemistry of the Atmosphere (Prof. Dr. J. P. Burrows) has coordinated the development of the SCIAMACHY and GOME satellite projects. Major research areas include atmospheric radiative transfer modelling, UV/visible/near IR satellite retrievals, remote sensing from ground and aircraft, in-situ chemical monitoring, chemistry-transport modelling, and data assimilation. The department of Climate Modelling (Prof. V. Eyring) analyses Earth system model (ESM) simulations in combination with observations to better understand and project the climate system and the anthropogenic climate change. The main task is the development and application of efficient methods and tools for ESM evaluation including the analysis of large data sets. The research activities are strongly linked to the World Climate Research Programme (WCRP), for example with substantial contributions to the Coupled Model Intercomparison Project (CMIP), the international climate and ozone assessments of the Intergovernmental Panel on Climate Change (IPCC), and the World Meteorological Organization (WMO).

Role in the project: UBREMEN will generate satellite-derived column-averaged dry-air CO_2 mole fraction, i.e., XCO_2, data products in WP1, developing diagnostics to evaluate the ESMs with 4C observations. UBREMEN will develop emergent constraints for carbon and biogeochemical feedbacks with satellite data in WP3.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Dr Michael Buchwitz (M) [4C WP1] [XCO_2 satellite data related contributions to Task 1.1 and 3.1] studied Physics at the University of Bremen. He is working on satellite remote sensing at the Institute of Environmental Physics of the University of Bremen since 1993 (except 2000-2001 where he was working as software developer and project manager at Interzart AG, a German e-commerce company). He is a specialist in radiative transfer and satellite remote sensing in the UV/visible/NIR/SWIR spectral region, and has participated in the specification of the SCIAMACHY instrument, mission planning, and detector selection. Currently, he is leading a research group at IUP focussing on the retrieval of CO_2, CH_4 and CO from satellites and aircraft. He participated/participates in various EU (e.g., EVERGREEN, AMFIC, ACCENT, CityZen, MACC, VERIFY, CHE) and ESA projects (e.g., PROMOTE, ADVANSE). He is co-proposer of CarbonSat and Science Leader of the ESA CCI GHG-CCI project and he is also leading the C3S_312a_Lot6 project delivering satellite CO_2 and CH_4 products for C3S. He is a member of ESA's CO_2 Monitoring Mission Advisory Group (MAG) and is (co)author of about 75 peer-reviewed publications.

Prof Dr Veronika Eyring (F) [4C WP3 co-lead] is Professor of Climate Modelling at the University of Bremen and maintains a strong collaboration with the National Center for Atmospheric Research (NCAR, USA) as Affiliate Scientist. She is also Head of the Earth system model evaluation and –analysis department at DLR. Her research focuses on Earth system modelling and evaluation with observations. She has authored many peer-reviewed journal articles and has contributed to the Intergovernmental Panel on Climate Change (IPCC) climate and World Meteorological Organization (WMO) ozone assessments since 2004. Veronika is the PI of the ESMValTool and is involved in the World Climate Research Programme (WCRP) through her roles as Chair of the CMIP Panel and member of the scientific steering committees for the Working Group on Coupled Modeling (WGCM), the WCRP Data Advisory Council's (WDAC) Observations for Model Evaluation Task Team, and the Working Group on Numerical Experimentation (WGNE)/WGCM Climate Model Diagnostics and Metrics Panel.

Dr Maximilian Reuter (M) [4C WP1&WP3] studied Physics at the Freie Universität Berlin where he also made his Ph.D. at the Institute for Space Sciences of Prof. Dr. Jürgen Fischer in 2005. From February 2006 to March 2007 he had a position at the German Weather Service (DWD) within the CM-SAF division (Satellite Application Facility on Climate Monitoring). His experience covers validation of satellite retrieved meteorological products, algorithm development, and optimal estimation based retrieval techniques. Since April 2007 he is working at the Institute of Environmental Physics (IUP) at University of Bremen focusing on the development of advanced satellite (SCIAMACHY, GOSAT, OCO-2) CO_2 retrieval algorithms. He is Deputy Project Manager of the GHG-CCI project of ESA's Climate Change Initiative (CCI) and Service

Manager of the C3S_312a_Lot6 project delivering satellite CO_2 and CH_4 products for the Copernicus Climate Change Service (C3S).

Bettina Gier (F) [4C WP1&WP3] studied Physics at the University of Heidelberg. From February 2017 to August 2017 she worked in the Earth System Model Evaluation Group at the Institute of Atmospheric Physics (IPA) of the German Aersospace Center (DLR), developing new diagnostics for the ESMValTool. She started her Ph.D. at the department of Climate Modelling at the Institute of Environmental Physics (IUP) of the University of Bremen in September 2017. Her focus is on carbon cycle feedbacks and emergent constraints utilizing both model data (e.g. CMIP5 Earth System Models) and observations (e.g. XCO_2 satellite data).

Dr Katja Weigel (F) [4C WP1&WP3] studied Meteorology at Kiel University and the University Centre in Svalbard. Her Ph.D. project on infrared limb sounding was carried out at Forschungszentrum Jülich in cooperation with the University of Wuppertal starting in September 2005. She recieved her Ph.D from University of Wuppertal in June 2009. She has been working at the Institute of Environmental Physics (IUP) at the University of Bremen since September 2009. Her main tasks included the retrieval and analysis of atmospheric water vapour profiles from SCIAMACHY limb data and the comparison of atmospheric trace gases from different satellite remote sensing data, in situ measurements, and model data. She participated in the DFG Reseach Unit SHARP (part I and II), several ESA Projects (SCILOV, SQWG, SPIN), and preparational studies for the new satellites S5 and S5P. She has joined the Climate Modelling Department in July 2018 to work with the ESMValTool on CMIP model evaluation.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. **Buchwitz, M.**, **Reuter, M.**, Schneising, O., Noël, S., **Gier, B.**, Bovensmann, H., Burrows, J. P., Boesch, H., Anand, J., Parker, R. J., Somkuti, P., Detmers, R. G., Hasekamp, O. P., Aben, I., Butz, A., Kuze, A., Suto, H., Yoshida, Y., Crosp, D., and O'Dell, C.: Computation and analysis of atmospheric carbon dioxide annual mean growth rates from satellite observations during 2003–2016, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-158, in review, 2018.
2. **Eyring, V.,** Righi, M., **Lauer, A**., Evaldsson, M., Wenzel, S., Jones, C., Anav, A., Andrews, O., Cionni, I., Davin, E. L., Deser, C., Ehbrecht, C., Friedlingstein, P., Gleckler, P., Gottschaldt, K. D., Hagemann, S., Juckes, M., Kindermann, S., Krasting, J., Kunert, D., Levine, R., Loew, A., Mäkelä, J., Martin, G., Mason, E., Phillips, A. S., Read, S., Rio, C., Roehrig, R., Senftleben, D., Sterl, A., van Ulft, L. H., Walton, J., Wang, S., and Williams, K. D.: ESMValTool (v1.0) – a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP, Geosci. Model Dev., 9, 1747-1802, 2016
3. Lauer, A., Jones, C., **Eyring, V.**, Evaldsson, M., Hagemann, S., Mäkelä, J., Martin, G., Roehrig, R., and Wang, S.: Process-level improvements in CMIP5 models and their impact on tropical variability, the Southern Ocean, and monsoons, Earth Syst. Dynam., 9, 33-67, 2018.
4. **Reuter, M., Buchwitz, M.**, Schneising, O., Noel, S., Bovensmann, H., Burrows, J. P.: A Fast Atmospheric Trace Gas Retrieval for Hyperspectral Instruments Approximating Multiple Scattering - Part 2: Application to XCO_2 Retrievals from OCO-2, Remote Sens., 9, 1102, doi:10.3390/rs9111102, 2017.
5. **Reuter, M., Buchwitz**, M., Schneising, O., Heymann, J., Bovensmann, H., and Burrows, J. P.: A method for improved SCIAMACHY CO_2 retrieval in the presence of optically thin clouds, Atmos. Meas. Tech., 3, 209-232, 2010.

5 relevant previous projects or activities, connected to the subject of this proposal

1. Earth System Model Evaluation Tool (ESMValTool) developer
2. Advanced Earth System Model Evaluation for CMIP (EVal4CMIP) funded by the Helmholtz-Society.
3. SHARP (DFG): SHARP - Stratospheric Change and its Role for Climate Prediction, DFG Research Unit 1095, http://www.geo.fu-berlin.de/en/met/sharp/index.html bringing together state-of-the-art climate models and observations, in particular those derived from satellite instruments to improve our understanding and ability to predict global climate change and its interplay with the stratosphere.

4. GHG-CCI (ESA): Greenhouse gas project of ESA's Climate Change Initiative (CCI) (http://www.esa-ghg-cci.org/) focussing on improving retrieval algorithms for the generation of satellite XCO_2 data products.
5. Copernicus Climate Change Service (C3S, EU/ECMWF): The greenhouse gas sub-project C3S_312a_Lot6 is led by UBREMEN and generates and delivers satellite-derived CO_2 and CH_4 atmospheric data products and supports related services.

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

The IUP has a large computational capacity, which is essential for extensive retrieval studies and for the processing and analysis of large data sets from satellite sensors. Each involved user at IUP has access to a state-of-the-art desktop computer and therewith access to a variety of workstations and servers. IUP operates a workstation cluster consisting of multicore workstations. There is also access to and expertise for the use of high performance parallel computers. IUP runs the
ESMValTool at supercomputing centers such as the German Climate Computing Center (DKRZ, Hamburg).

Partner name: University of Bern (UBERN)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The host institution will be Climate and Environmental Physics, Physics Institute at the University of Bern (UBERN). With 17,500 students and 2,700 PhD students, UBERN is the third largest university in Switzerland and is ranked 105 in The World University Rankings 2018. The university's comprehensive offering includes 8 faculties with more than 150 institutes. UBERN hosts several internationally recognised research centres, such as the Oeschger Centre for Climate Change Research which bundles the research activities on climate change across four faculties. UBERN is very experienced in managing EU Grants and has been involved in projects since FP3. For FP7 and Horizon 2020, this amounts to about 130 and 60 grants, respectively. UBERN has endorsed the "The European Charter for Researchers" and "The Code of Conduct for the Recruitment of Researchers". European grants are managed by the Euresearch office, which is part of the Grants Office. For FP7, UBERN has 109 completed projects. UBERN currently hosts about 80 EU-funded projects from FP7 and Horizon 2020.

Climate and Environmental Physics **(**CEP), UBERN, has more than 40 years of experience in modelling biogeochemical cycles, climate, and the Earth System. CEP has pioneered reduced form models and Earth System Models of Intermediate Complexity and has extensive experience in applying state-of-the-art Earth System models. The overall focus of the Climate and Environmental Physics department (CEP) is to understand the environment, its present and past and its evolution on time scales from decades to one million years. The department currently has a scientific and technical staff of around 60 people. During the three years from 2015 to 2017, 132 papers have been published and 10 PhD theses completed. 9 papers were published in Science and or Nature journals. Members of CEP have been involved in all major IPCC Assessments since the First Assessment Report and contributed to IPCC as Co-Chair of Working Group I, as Vice Chair of WGI, and as coordinating lead authors, lead authors and review editors in various Reports and Technical Papers.

Role in the project: UBERN will co-lead WP3 and contribute with two state-of-the art Earth System Models (NCAR CESM2 and the GFDL ESM2M) and with its Bern3DLPX Earth System Model of Intermediate Complexity. In WP1, UBERN will contribute to the improvement of understanding the contemporary carbon cycle by assessing the budget of atmospheric $^{13}CO_2$, performing isotope-enabled industrial period simulations and contribute to model evaluation and the detection and attribution of anthropogenic signals. In WP3, UBERN will contribute, identifying new emergent constraints for carbon and biogeochemical feedbacks, improve estimates of climate metrics (TCRE), and develop protocols and perform adaptive scenarios towards meeting the Paris Agreement climate ambitions. UBERN supports the project's outreach activities and is co-chairing Carbon Cycle ScienceBrief.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities
Professor Thomas Frölicher (M) [4C WP3 co-lead] is the head of the Ocean Modelling group and currently an SNSF assistant professor. He authored or co-authored 45 peer-reviewed publications, including seven studies published in Nature (and its offsprings) and Science. Many of the publications include analysis of simulations with similar coupled Earth System Models as the one that will be used in this project. He is also the lead author of chapter six of the upcoming IPCC Special Report on the Ocean and Cryosphere in a changing climate, and contributed to the fifth assessment report of working group II of the IPCC. He is also the recipient of a SNSF Ambizione fellowship and has co-organized the World Climate Research Program workshop on 'Extending the climate-carbon cycle feedback framework' in 2018. **Professor Fortunat Joos (M)** [4C project PI for UBERN, WP1&3] is head of the group Earth System Modelling – Biogeochemical Cycles and has 30 years of experience in modelling the carbon cycle in the Earth System. He authored or co-authored more than 150 peer-reviewed publications and is recognized as "Highly Cited Researcher" by Thompson Reuters. He served as author and Vice Chair of Working Group I in previous IPCC assessments. He is a fellow of the American Geophysical Union. He served as President of the Oeschger Centre for Climate Change Research from 2010 to 2017 and chaired the anniversary 10th International Carbon Dioxide Conference in 2017. He is a SSC member of the CMIP6 Ocean Model Intercomparison Project. He contributed as PI and WP leader to several FP6 and FP7 projects on Climate and Earth System Science (CAROCHANGE, CARBOOCEAN, EUR-OCEAN, MARiRON, GAINS-ASIA, NICE, and EPOCA).
5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content
1. **Frölicher T. L.**, D. J. Paynter, 2015, Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales. *Environmental Research Letters*, 10, 075002 2. **Frölicher, T. L.**, J. L. Sarmiento, D. J. Paynter, J. P. Dunne, J. P. Krasting, M. Winton, 2015, Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *J. Climate*, 28, 862-886 3. Palter, J., **T. L. Frölicher**, D. Paynter, J. John, Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5K warming. Earth System Dynamics, 9, 817-828, 2018. 4. Keller, K. M., S. Lienert, A. Bozbiyik, T. F. Stocker, O. V. Churakova, D. C. Frank, S. Klesse, C. D. Koven, M. Leuenberger, W. J. Riley, M. Saurer, R. Siegwolf, R. B. Weigt, F. Joos, "20th century changes in carbon isotopes and water-use efficiency: tree-ring-based evaluation of the CLM4.5 and LPX-Bern models", *Biogeosciences, 14*, 2641-2673, 2017. 5. Battaglia, G., F. Joos, "Hazards of decreasing marine oxygen: the near-term and millennial-scale benefits of meeting the Paris climate targets ", *Earth System Dynamics*, 9, 797-816, 2018.
5 relevant previous projects or activities, connected to the subject of this proposal
1. Anthropogenic carbon and heat uptake by the Southern Ocean (PZ00P2_142573): The project (2013-2016) funded by the Swiss National Science Foundation provided a better understanding of the exact processes governing the magnitude and regional distribution of heat and carbon uptake by the ocean, thereby pinning down one of the greatest sources of uncertainty in predictions of the fate of anthropogenic carbon and of the climate. 2. CARBOCHANGE (264879): This FP7 project provided process-based quantification of net ocean carbon uptake under changing climate conditions using past and present ocean carbon cycle changes for a better prediction of future ocean carbon uptake. The project improved the quantitative understanding of key biogeochemical and physical processes through a combination of observations and models and quantified large-scale integrative feedbacks of the ocean carbon cycle to climate change and rising carbon dioxide concentrations as well as the vulnerability of the ocean carbon sources and sinks in a probabilistic sense and under climate stabilization.

3. bgcCEP (200020_172476): This project (2017-2021) funded by the Swiss National Science Foundation integrates information from paleo proxy data and the instrumental record into Earth system models to advance the quantitative and qualitative understanding of biogeochemical-climate feedbacks and to improve Earth system projections. A focus is on the greenhouse gases carbon dioxide, methane, and nitrous oxide and their land and ocean sources and sinks over the past 20,000 and the last million years.

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work
CEP maintains its own Linux Cluster, has access the UBERN Linux Cluster and, maintains within the Oeschger Centre two one Petabyte data storage facility. CEP has access to the High Performance Computing Infrastructure at the Swiss National Supercomputing Centre. This will allow CEP to perform model simulations, and store and analyses results for 4C.

Partner name: CICERO Center for International Climate Research (CICERO)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

CICERO Center for International Climate Research is a leading inter-disciplinary climate research institute in the Nordics, with departments on the climate sciences, climate economics, climate policy and climate communication. Researchers undertake projects funded primarily by the EU Framework Programmes and the Research Council of Norway, with smaller funding from Government ministries and other national and international programmes or organisations. CICERO researchers regularly published in top academic journals in a range of fields (Science, Nature, etc) and has the highest publication ranking amongst the Norwegian environmental institutes. Communication, stakeholder management and process facilitation is of core importance to CICERO from its founding, with most CICERO projects involving dedicated communication and dissemination activities. CICERO participates in a broad network of national and international research communities: IPCC assessment reports (AR6 WGI vice-chair, SR15 Review Editor, six lead authors), global change programmes (e.g., Future Earth, Global Carbon Project) and EU research (eg Joint Programming Initiatives). CICERO has around 75 staff, 60 of which are research staff, 10 in administration and 5 dedicated to communication.

CICERO has made an important contribution to the Global Carbon Project (GCP), particularly the Global Carbon Budget and publishing high-level analysis and synthesis papers on near-term projections of the carbon budget, emission scenarios, and the remaining carbon budget concept. CICERO places strategic importance on synthesis, communication, and outreach activities, and is developing new concepts for better engagement with users via a strategic project “Rapid Response for Climate and Energy Analysis”. CICERO’s competence is relevant for many tasks in 4C, but will focus on leading tasks in WP4 and contributing to the global carbon and oxygen budget (WP1) and the transient climate response to cumulative emissions (WP3).

Role in the project: CICERO will co-lead WP4, ensuring optimal synthesis, dissemination and policy dialogue. CICERO will also contribute to WP1 in the development of O_2 and ^{13}C budgets constraints on the carbon cycle and to WP3 in the assessment of TCRE, accounting for non-CO_2 forcing.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Glen Peters (M) [WP4 co-lead] is a Research Director at CICERO, where he has worked for ten years and managed several large interdisciplinary research projects. He is a worldwide authority on emission drivers and scenarios, demonstrated via highly-cited articles in high-level journals. Dr Peters has played an important role in the Global Carbon Budget in the last eight years, coordinating data and performing analysis on emission sources, and writing several synthesis articles. He has just completed a six-year (maximum) term on the Scientific Steering Committee of the Global Carbon Project. He is a Lead Author for the IPCC Sixth Assessment Report on emission scenarios (WG3 Chapter 3).

Robbie Andrew (M). [4C WP1] Leading authority in emission statistics and emission drivers, with several publications in high-level journals. Andrew performs most data analysis, management, and graphical presentation for the emission source component of the Global Carbon Budget. Andrew also has extensive experience on agricultural emissions through his previous employment in New Zealand and ongoing CICERO research projects.

Ms. Iselin Rønningsbakk (F) [4C WP4] is a senior communications advisor with an MSc in Politics and Government in EU from LSE and a double degree MA through Erasmus in journalism and media studies from Universities of Hamburg, Århus and Amsterdam. For the past two years she has worked as communications advisor for Mid-Norway's regional Brussels office where she was responsible for all communications activities, including the website, a monthly newsletter, social media and the running of a Horizon 2020 network. Previous work experience includes being energy reporter for Montel and information advisor for EFTA. This year she completed a college course in EU project management and she has completed several courses in Horizon 2020 management offered by the Norwegian research council.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. Peters GP, LeQuéré C, Andrew RM, Canadell JG, Friedlingstein P, Ilyina T, Jackson RB, Joos F, Kosbakken JI, McKinley GA, Sitch S, Tans P (2017), Towards real-time verification of CO_2 emissions, *Nature Climate Change*, doi:10.1038/s41558-017-0013-9.
2. Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, Pongratz, J., Manning, A.C., Korsbakken, J.I., Peters, G.P., et al. (2018), Global Carbon Budget 2017, *Earth System Science Data*, vol. 10, no. 1, pp. 405-448.
3. Peters, 2018, Beyond Carbon Budgets, *Nature Geoscience*, 11, 378-380.
4. Peters, 2016. The 'best available science' to inform 1.5°C policy choices, *Nature Climate Change* 6, 646-649
5. Global Carbon Project (annual releases), data portal, website, graphical material, visualisations, synthesis reports, etc. http://www.globalcarbonproject.org/carbonbudget/index.htm

5 relevant previous projects or activities, connected to the subject of this proposal

1. IPCC AR6 Lead Author, WGIII chapter 3 "Mitigation pathways compatible with long-term goals"
2. Horizon 2020 (2018-2021): Observation-based system for monitoring and verification of greenhouse gases (**Work Package Leader**)
3. Various Norwegian sources (2012-2016): Support for the Global Carbon Project (**Project Leader**)
4. Strategic Institute Funding, Norwegian Research Council (2016-2019): Rapid Response for Climate and Energy Policy (**Project Leader**)
5. 2011-2020: Strategic Challenges in International Climate and Energy Policy (**Participant**)

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

Not relevant for CICERO's contribution to 4C.

Partner name: The Chancellor Masters and Scholars of the University of Oxford (UOXF)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The University of Oxford is consistently ranked amongst the top-ten research universities in the world. With substantial recent and ongoing investment in physical climate science research, faculty and infrastructure, the University now employs >180 staff and PhD students directly working within climate science research groups. Atmospheric, Oceanic and Planetary Physics within the Department of Physics and the Environmental Change Institute (ECI), School of Geography are at the core of a physical climate science initiative at Oxford. Myles Allen the former academic convener of the Oxford Climate Research Network (www.climate.ox.ac.uk). The University has formal links to the European Center for Medium Range Weather Forecasting, and NERC's National Centre for Atmospheric Science, NERC's National Centre for Earth Observations alongside strong collaborative links with the UK Met Office formalized through membership in the Met Office's Academic Partnership scheme.

Role in the project: UOXF main role will be in WP3, on the reassessment of TCRE including non-CO_2 emissions, and on the development of the adaptive scenarios. UOXF will also contribute to WP2, on the detection of peak emissions and to WP4 on synthesis and dissemination, supporting the IPCC assessment.

Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities

Myles Allen (M) [4C Task 3.2 lead] is Professor of Geosystem Science in the Environmental Change Institute, School of Geography and the Environment and Department of Physics, University of Oxford. His research focuses on how human and natural influences on climate contribute to observed climate change and risks of extreme weather and in quantifying their implications for long-range climate forecasts. He has served on the Intergovernmental Panel on Climate Change as Coordinating Lead Author on the Special Report on 1.5°C, Lead Author on Detection of Climate Change and Attribution of Causes for the 3rd and 5th Assessments in 2001 and 2013, as Review Editor on Global Climate Projections for the 4th Assessment in 2007, and on the IPCC Synthesis Report Core Writing Team in 2014. He proposed a novel usage of Global Warming Potentials to account for the different behaviour of stock versus flow pollutants in papers in 2016 and 2018; led and co-authored two papers in 2009 identifying the cumulative impact of carbon dioxide emissions on global temperatures and their policy implications; and leads the climateprediction.net project, using distributed computing to run the world's largest ensemble climate modelling experiments.

Michelle Cain (F) [4C WP3] is an Oxford Martin Fellow and Science and Policy Research Associate based jointly in the Oxford Martin School and Environmental Change Institute at the University of Oxford. Her current work is about the impact of short lived climate forcers on temperature and climate, with a focus on developing and applying metrics that inform climate policies. She received her PhD from the University of Reading in 2010, followed by postdoctoral positions at the University of Cambridge working on the chemistry and transport of air pollution and greenhouse gases, with a particular focus on methane emissions. She spent 18 months seconded to the UK Department for the Environment, Food and Rural Affairs to work on the use of air quality modelling for government policy purposes.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content

1. Millar, R.J., Fuglestvedt, J.S., Friedlingstein, P., Rogelj, J., Grubb, M.J., Matthews, H.D., Skeie, R.B., Forster, P.M., Frame, D.J. & Allen, M.R. 2017, "Emission budgets and pathways consistent with limiting warming to 1.5 °C", Nature Geoscience, vol. 10, no. 10, pp. 741-747.
2. Allen, M. R., Shine, K. P., Fuglestvedt, J. S., Millar, R. J., Cain, M., Frame, D. J., & Macey, A. H. (2018). A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. Npj Climate and Atmospheric Science, 1(1), 16. https://doi.org/10.1038/s41612-018-0026-8
3. MR Allen, JS Fuglestvedt, KP Shine, et al, New use of global warming potentials to compare cumulative and short-lived climate pollutants, Nature Climate Change, 6, 773-776, 2016.
4. M. R. Allen et al: Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458:1163-1166, 2009 (Cover).
5. Cain, M., Warwick, N. J., Fisher, R. E., Lowry, D., Lanoisellé, M., Nisbet, E. G., et al., (2017). A cautionary tale: A study of a methane enhancement over the North Sea. Journal of Geophysical Research: Atmospheres, 122(14), 7630–7645. https://doi.org/10.1002/2017JD026626

5 relevant previous projects or activities, connected to the subject of this proposal

1. Coordinating Lead Author, Chapter 1, Framing and Context, of the IPCC Special Report on 1.5C, 2017-2018 (Allen)
2. Lead Author on Detection of Climate Change and Attribution of Causes for the 3rd and 5th Assessments in 2001 and 2013 (Allen)
3. "Climateprediction.net - distributed computing for global climate research", collaborative project (2000 present, overall budget c. ¬£4m), performing large-scale Monte Carlo simulation of climate change 1900 - 2100 using idle CPU on personal computers volunteered by the general public. (Allen, PI)
4. Member of the US National Academies of Science Technology and Medicine Committee on Methods of Evaluating the Social Cost of Carbon (Allen)
5. Consultancy for JPI-Climate (a European Commission Joint Programming Initiative on "Connecting Climate Knowledge for Europe") for a series of workshops and a report addressing the question of what is required for the "balance of sources and sinks of greenhouse gases" that is outlined in the Paris Agreement, in particular relating to the role of non-CO_2 forcings (Cain)

Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work

N/A

Partner name: Commissariat à l'énergie atomique et aux énergies alternatives (CEA)

Description of the legal entity and its main tasks, with an explanation of how its profile matches the tasks in the proposal

The Laboratory of Climate and Environmental Sciences (French: Laboratoire des Sciences du Climat et de l'Environnement, LSCE), created in 1998 is both an institution and joint research unit (UMR 8212) of the French Alternative Energies and Atomic Energy Commission (French: Commissariat à l'énergie atomique et aux énergies alternatives, CEA), the French National Centre for Scientific Research (French: Centre national de la recherche scientifique, CNRS), and the University of Versailles Saint-Quentin (UVSQ). CEA is the legal entity that represents the LSCE within this project.

The LSCE aims to understand past, present, and future biogeochemical cycles and climate characteristics and evolution and to predict the changes our planet will have to face in the next decades and centuries due to climate change forced by increasing greenhouse gases. The LSCE has participated in numerous national and international research and private sector projects since its foundation about activities related to this proposal.

With more than 310 staff members, the LSCE is an associated laboratory of the Institute Pierre Simon Laplace (IPSL) that brings together nine research laboratories working on the global environment. Through the IPSL, the LSCE participates to two French laboratories of excellence (LABEX) using the IPSL Climate model, one of the top 10 most powerful and complete climate models in the world. The LSCE contributes greatly to the IPSL strategy for the study of the "Earth System" at various spatial and temporal scales.

The LSCE has a leading international expertise in carbon cycle and climate modelling, the assimilation of data on land surface properties, as well as measurements of greenhouse gases in the atmosphere and inversions of their fluxes going from regional to national and global scales. The LSCE has been heavily involved in the Global Carbon Project, as is illustrated by globalcarbonatlas.org, an online platform to explore global and regional carbon data that it has developed through a philanthropic grant. It has strong participation in PMIP and CMIP projects on numerical simulation of the climate, and control of the modelling infrastructure project IS-ENES, has a leading role in the creation of the Climate-JPI, as well as the coordination of Charmex, and contribution to SICMED MERMEX. The LSCE is also a major contributor to the last IPCC report.

The LSCE produces more than 250 publications per year, with a significant fraction published in the most prestigious international journals in the discipline, such as Nature, Science, PNAS, NatureGeoscience, with a higher than average impact factor of 8. The average number of citations per paper at LSCE is approximately

14. Additionally, 31% of publications the LSCE are among the 10% most cited publications in the world in Geosciences and 6% are part of the 1% most cited publications. **Role in the project:** CEA will contribute to WP1, WP2 and WP3, leading the evaluation task (T1.4) in WP1. CEA will contribute to historical simulations, analysis and process attribution with the ORCHIDEE land model and with the IPSL-ESM (jointly with ENS), leading the evaluation of the land and ocean carbon cycle. CEA will also develop new obsravtional constraints on the land carbon cycle. CEA will contribute to the decadal predictions with the IPSL-ESM (jointly with ENS) in WP2 and to the adaptive scenarios simulations in WP3.
Curriculum vitae or description of the profile of the persons, including their gender, who will be primarily responsible for carrying out the proposed research and/or innovation activities
Professor Philippe Ciais (M) [4C Task 1.4 lead] works in the global biogeochemical cycles and transfers department of LSCE where the project will be hosted, is the author of 650 peer-reviewed publications (H-index= 105; cited 29000 times). P.C. is among the top-1% most-cited scientists in both Geosciences and Ecology, author of more than 60 publications in Nature, Science and high-impact journals, and ranked most productive scientist in the field of climate change1. He mentored 40 PhDs and 30 post-doctoral fellows and obtained the EGU Copernicus Medal in 2016. International experience: P.C. co-chaired the Global Carbon Project (GCP) and the Carbon Strategy of the Group on Earth Observation, and acted as Convening Lead Author of the IPCC in the 5th Assessment Report. European experience: P.C. coordinated projects in FP-5, project components in CARBOEUROPE (FP-6) and GHG-EUROPE (FP-7) and the GEOMON (FP-7) project. P.C. coordinated of the Preparatory Phase of the ICOS Research Infrastructure in 2007, establishing a dialogue with the EU and member states representatives at ministerial level, which led to the successful establishment of the operational Infrastructure involving 17 countries. P.C. is a co-laureate of the ERC-synergy Imbalance P grant on the phosphorus interactions in the Earth system. P. C. will lead Task 1.4 in the 4C project. **Dr. Philippe Peylin (M)**. [4C WP1-3] is head of the "Atmosphere Surface Interface Modeling" team of CEA-LSCE, which includes 20-25 scientists and students. He is a research scientist working on the Carbon Cycle with a 15-year strong expertise in the development of terrestrial ecosystem models and the application of data assimilation techniques to improve the simulations of carbon, water and energy balances. He is currently coordinating the development of the ORCHIDEE land surface model (http://labex.ipsl.fr/orchidee/; to be used in 4C), the land surface component of the IPSL Earth System Model, developed across several French and international laboratories and central to the 4C project. He coordinated/coordinates several research projects, including an EU-funded FP7 project, CARBONES, dedicated to a 30-year reanalysis of the carbon cycle and the on-going H2020 VERIFY project on monitoring GhG fluxes from land, ocean and atmospheric observations. He published around 120 peer-reviewed papers. **Dr. Bertrand Guenet (M)** [4C WP1&2] research is mainly focus on the soil biogeochemistry in a global change context at large scales using mainly land surface models but also more simple and theoretical models. He's interested in the full cycle of soil elements (carbon, nitrogen, phosphorous, etc.) including lateral fluxes through run off or erosion and the impact of such lateral fluxes on aquatic ecosystems functioning. he also participates to meta-analysis and laboratory experiments to better understand the process and their impacts at large scales. He started to work using laboratory experiments to better understand the soil carbon emissions process and in particular the priming effect. Now he's mainly working on land surface modeling with a particular interest on soil carbon modeling. Since 2009 he has published 47 papers in SCI Journals cited 1004 times, his impact factor is of 15 with more than 90% of his manuscripts are published in top 10% journals (according to their ranking in one of the ISI categories). **Dr Nicolas Vuichard (M)** [4C WP1&3] is a research scientist, expert in modeling carbon and nitrogen fluxes in terrestrial ecosystems, with an emphasis on managed lands such as croplands and pastures. He has been involved in several European projects and Model Intercomparison Projects aiming mostly at better quantifying the land/atmosphere carbon and water fluxes, from seasonal to multi-annual time scales, and at continental scale. Recently, he coordinated the development of an ORCHIDEE model version coupling the nitrogen and carbon cycles. He contributed to ~50 A-ranking publications cited 2000 times, and has an impact factor of 21.

5 relevant publications, and/or products, services (including widely-used datasets or software), or other achievements relevant to the call content
1. Guenet, B., Camino-Serrano, M., Ciais, P., Tifafi, M., Maignan, F., Soong, J.L., et al. (2018). Impact of priming on global soil carbon stocks. Glob. Chang. Biol., 24, 1873–1883. 2. Walsh, B., P. Ciais, I. A. Janssens, J. Penuelas, K. Riahi, F. Rydzak, D. P. van Vuuren, and M. Obersteiner (2017), Pathways for balancing CO_2 emissions and sinks, Nature Communications, 8, 12. 3. Peylin, P., Bacour, C., MacBean, N., Leonard, S., Rayner, P. J., Kuppel, S., Koffi, E. N., Kane, A., Maignan, F., Chevallier, F., Ciais, P., and Prunet, P., 2016: A new stepwise carbon cycle data assimilation system using multiple data streams to constrain the simulated land surface carbon cycle, Geosci. Model Dev., 9, 3321-3346. 4. Ciais, P., T. Gasser, J. D. Paris, K. Caldeira, M. R. Raupach, J. G. Canadell, A. Patwardhan, P. Friedlingstein, S. L. Piao, and V. Gitz (2013), Attributing the increase in atmospheric CO_2 to emitters and absorbers, *Nature Climate Change*, *3*(10), 926-930. 5. Ciais, P., et al. (2008), Carbon accumulation in European forests, *Nature Geoscience*, *1*(7), 425-429.
5 relevant previous projects or activities, connected to the subject of this proposal
1. CRESCENDO (641816): This H2020 project facilitates a coordinated European contribution to the 6th Coupled Model Intercomparison Project (CMIP6) where the climate research community compares a range of International Earth System Models using common sets of experimental protocols, to improve our knowledge of the Earth's climate processes and provide the best possible future projections to governments and decision-makers. CRESCENDO in particular better informs a number of key Model Intercomparison Projects (MIPs) where biogeochemical and aerosol components are of critical importance to delivering realistic future projections. Such components include: the terrestrial and marine carbon cycle, vegetation processes, permafrost, atmospheric chemistry and aerosols. 2. HELIX: EU-funded collaborative research project assessing the potential impacts of climate change. Scientists from 16 organisations worldwide have worked together to develop a number of future scenarios of the natural and human world as a consequence of 1.5°C, 2°C, 4°C and 6°C global warming. HELIX results are communicated to to decision makers and the public to help understand what kind of climate change impacts we wish to avoid and make adapting to our changing climate more understandable and manageable. 3. VERIFY: This H2020 project will develop a pilot monitoring system based on land, ocean and atmospheric observations to support estimates of greenhouse gas budgets established by countries to the UN Climate Change Convention secretariat. Research institutes across Europe and national inventories agencies being partners of the project are working together to advance the use of observations and models for quantifying space-time patterns and national budgets of GHG emissions and sinks, with a focus on CO_2, CH_4 and N_2O. The project is coordinated by CEA. 4. IMBALANCE-P: This ERC Synergy project assesses the responses of ecosystems and society in a world increasingly rich in nitrogen (N) and C but limited in Phosphorus (P) is an earthbound and finite element and the prospect of constrained access to mineable P resources has already triggered geopolitical disputes. In contrast to P, availabilities of carbon (C) and nitrogen (N) to ecosystems are rapidly increasing in most areas of the globe. The resulting imminent change in the stoichiometry of available elements will have no equivalent in the Earth's history and will bear profound, yet, unknown consequences for life, the Earth System and human society. The IMBALANCE-P-team, gathers 4 researcher groups in the fields of ecosystem diversity and ecology, biogeochemistry, Earth System modelling, and global agricultural and resource economics, will address this Earth System management challenge by providing improved understanding and quantitative foresight to mitigate the consequences of stoichiometric imbalances.
Description of any significant infrastructure and/or any major items of technical equipment, relevant to the proposed work
N/A

4.2 Third parties involved in the project (including use of third party resources)

Participant 3: ENS

Does the participant plan to subcontract certain tasks (please note that core tasks of the project should not be sub-contracted)	N
Does the participant envisage that part of its work is performed by linked third parties	Y
ENS is the legal body representing the Laboratoire de Météorologie Dynamique (LMD) in this project. LMD is a UMR (unité mixte de recherche – UMR8539) and includes both CNRS and ENS staff. In order to allow the participation of CNRS staff in the project, they are included as a linked Third Party of ENS. The French National Centre for Scientific Research (CNRS) is a government-funded research organization under the administrative authority of French Ministry in charge of research. CNRS is the main fundamental research organization in Europe and is largely involved in national, European, and international projects covering all fields of knowledge. CNRS is organized in 1211 laboratories, either intramural or in partnership with universities, research organizations and Ecole like ENS. The CNRS has a strong experience and capacity in management of EU funded projects. *CNRS staff will contribute to the project as follows, with an estimated budget of €154,382:* *Laurent Bopp :* *WP1 - T1.3 Historical simulations of the ocean carbon cycle (2 PM)* *WP2 - T2.1. Assessment of the potential predictability of carbon sinks and of their main drivers (5 PM)* *Patricia Cadule :* *WP1 - T1.3: Historical simulations of the Earth's carbon cycle with ESMs (5 PM)* *WP2- T2.3 Predictability of the carbon cycle using CO_2 emission-driven ESMs (2 PM)* *WP2 - T2.4. Decadal predictions of future atmospheric CO_2 over the stocktake period following future climate change scenario (3 PM)*	
Does the participant envisage the use of contributions in kind provided by third parties (Articles 11 and 12 of the General Model Grant Agreement)	N
Does the participant envisage that part of the work is performed by International Partners (Article 14a of the General Model Grant Agreement)?	N

Participant 6: BSC

Does the participant plan to subcontract certain tasks (please note that core tasks of the project should not be sub-contracted)	N
Does the participant envisage that part of its work is performed by linked third parties	N
Does the participant envisage the use of contributions in kind provided by third parties (Articles 11 and 12 of the General Model Grant Agreement)	Y

BSC applies a Third Party modality with the Institut Català de Recerca i Estudis Avançats (ICREA), where the third party makes its resources available to the beneficiary under Article 12 of the Grant Agreement - Use of in-kind contributions provided by third parties free of charge. According to this situation, ICREA will not carry out any part of the work and just lends resources to the beneficiary. These resources are directly used by the beneficiary, the work is performed in its premises and there is no reimbursement by the beneficiary to the third party. The third party makes available resources (dedicated time of Prof. Francisco J. Doblas-Reyes, who is employed by ICREA) to the beneficiary, which does not reimburse the cost to the third party, but which charges the costs of the third party as an eligible cost of the project. Its costs will be declared by the beneficiary in its Form C but will be recorded in the accounts of the third party. ICREA resources will be available for the whole duration of the project, especially for the activities in Work Package 2, with an approximate allocation of 1 PM per year / or 4 PMs (for the whole duration of the project) at an approximate cost of €18,000..	
Does the participant envisage that part of the work is performed by International Partners (Article 14a of the General Model Grant Agreement)?	N

No other participant foresees the use of Third Parties.

5 Ethics and Security

5.1 Ethics

Ethics considerations relating to this project are restricted to the processing and protection of personal data. Workshops and seminars will be organized with the participation of experts and policymakers. An online survey also aimed at professionals and opinion editorials will be produced for communication activities. We will inform participants that they are part of an ongoing research project.

Contact information for workshop and seminar participants may be collected through actions such as: project mailing lists, website contact form, carbon outlooks subscription, online surveys, and e-mail contacts with stakeholders interested in 4C events. The personal data collected will relate to professional information (name and surnames, position, institution and contact information).

Besides professional information, during the events planned across the project lifetime, pictures and videos may be taken, always with the informed consent of the people recorded.

We will provide a copy of the procedures and criteria that will be used to identify/recruit research participants, including informed consent regarding the processing of personal data, templates of the informed consent forms and information sheets and a description of the security measures of any partners involved in collected and using this data.

5.2 Security

The project raises no security issues.

6 Annex 1: References

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