White Paper on WCRP Grand Challenge – Draft, February 29, 2016

Biogeochemical Cycles and Climate Change

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Processes governing natural biogeochemical cycles and feedbacks currently remove anthropogenic carbon dioxide from the atmosphere, helping to limit climate change. These mitigating effects may significantly reduce in a warmer climate, amplifying risk of climate change and impacts. How the biogeochemical cycles and feedbacks will change is very uncertain.

Our grand challenge is to understand how these biogeochemical cycles and feedbacks control greenhouse gas concentrations and impact on the climate system.

This Grand Challenge will be addressed through community-led research initiatives on the following key guiding questions:

- **Q1: What are the drivers of land and ocean carbon sinks?**
- **Q2: What is the potential for amplification of climate change over the 21st century via climate-biogeochemical feedbacks?**
- **Q3: How do greenhouse gases fluxes from highly vulnerable carbon reservoirs respond to changing climate (including climate extremes and abrupt changes)?**

1. Background

The land and ocean biogeochemical cycles are key components of the Earth's climate system. The surface fluxes of many greenhouse gases and aerosol precursors are controlled by biogeochemical and physical processes and are sensitive to changes in climate and atmospheric composition. Most importantly, biogeochemical processes control atmospheric concentrations of the main greenhouse gases (CO_2, CH_4 and N_2O). Plants, soils and permafrost on the land together contain at least five times as much carbon as the atmosphere, and the global ocean contains at least fifty times more carbon than the atmosphere. Based on the 2015 Global Carbon Budget estimates, since 1870, CO_2 emissions from fossil fuel combustion have released about 400±20 GtC (Gigatonnes carbon) to the atmosphere, while land use change is estimated to have released an additional 145±50 GtC. Of these cumulative anthropogenic CO_2 emissions, 230±5 GtC have accumulated in the atmosphere, while the ocean and land ecosystems have taken up 155±20 GtC and 160±60 GtC, respectively. Land and oceans are hence absorbing around half of the carbon emitted from human activity, significantly mitigating the build up of CO_2 in the atmosphere and climate change. In the absence of these carbon sinks, current atmospheric CO_2 would already be about twice the pre-industrial CO_2 concentration with an associated global warming likely above 2°C. However, substantial uncertainty remains about the magnitude of these carbon sinks, how they currently operate, and whether they will continue to be as effective as climate changes. When climate models first included climate-carbon cycle feedbacks, they indicated the potential for these carbon sinks to be significantly weakened under global warming, accelerating atmospheric CO_2 increases and hence global

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[*] Acknowledgment: G. Brasseur, V. Brovkin, P. Canadell, D. Carlson, P. Ciais, B. Collins, N. Gruber, N. Harris, M. Hegglin, G. Hugelius, C. Jones, C. LeQuéré, V. Ramaswamy and C. Sabine

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warming over the 21st century. A subsequent inter-comparison of first-generation coupled climate-carbon cycle models (C^4MIP) showed carbon cycle feedbacks to be a key uncertainty in climate projections, of similar importance as uncertainty arising from physical feedbacks. The CMIP5 Earth System Model (ESM) simulations assessed in the IPCC AR5 still showed significant uncertainty, particularly for the land components. Large uncertainties remain about future fluxes from tropical ecosystems, about the possible fluxes of CO_2 and CH_4 from thawing permafrost and wetlands, and about the current and future role of nutrients as growth limiting factors. Most models identify the Southern Ocean as a key player in global uptake of anthropogenic carbon but the strength of this important ocean sink and its response to climate change and variability are still poorly assessed and represented in ESMs. Limitations in the understanding of the carbon sinks have crucial implications for climate policy, such as the estimate of the remaining CO2 emissions compatible with a global warming target of 2°C (or 1.5°C as proposed by the UNFCCC COP21).

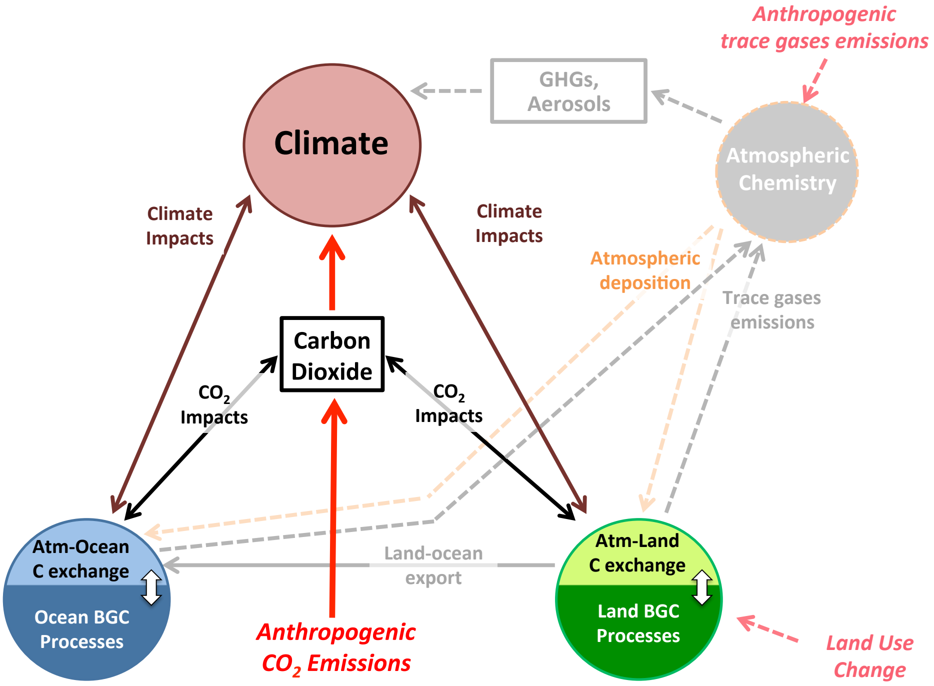

Figure 1: Overview of biogeochemical processes and feedbacks in the Earth system. *Growing fossil fuel carbon emissions increase atmospheric* CO_2 *concentration, thereby affecting the physical climate system (red arrows). Ocean and land biogeochemical processes and exchange of carbon with the atmosphere are directly affected by the state of the physical climate system (brown arrows) and* CO_2 *concentration via dissolution of* CO_2 *in the ocean and* CO_2 *fertilization of terrestrial vegetation (black arrows). In return, ocean and land affect climate and atmospheric* CO_2 *via biophysical and biogeochemical feedbacks, respectively (same brown and black arrows). Additionally, land and ocean pools of carbon and nutrients are affected by their transport from land into the ocean (grey arrow). Land and ocean biogeochemical processes are affected by atmospheric deposition (orange dashed arrows); they affect atmospheric chemistry via emissions of trace gases (grey dashed arrows) and thus further impact on the physical climate state.*

2. The Grand Challenge

The grand challenge over the next 5-10 years will be to accelerate progress in assessing the controls of biogeochemical cycles and feedbacks on GHG concentrations and climate by addressing three guiding questions as outlined below. Although this Grand Challenge is about Biogeochemical Cycles, the main area of research will be on the global carbon cycle, and more precisely on better *understanding major sources and sinks of CO_2 in a changing environment. The reason is twofold: CO_2 is the dominant GHG of anthropogenic origin, and it is by far the dominant gas exchanged between the atmosphere, the land and the oceans. We identified three overarching guiding questions that need to be addressed in priority.*

Question 1: What are the drivers of ocean and land carbon sinks?

There are major gaps in our understanding of the physical and biogeochemical processes that are driving these carbon sinks. The strength of the ocean carbon sink is determined by chemical reactions in seawater, biological processes such as photosynthesis and respiration, and physical processes, including ocean circulation and vertical mixing. But even though these key mechanisms are known, there are large uncertainties with regard to their strength, as well as regional and interannual variability. What is the relative role of ocean circulation and biology in governing the Southern Ocean carbon sink? What is the relationship between the ocean uptake of carbon and heat? For terrestrial systems, the issue is even more fundamental as the main barriers relate to the actual processes driving the sinks. What is the actual strength of the CO_2 fertilization? What is the effect of land use change on terrestrial carbon? What are the effects of climate change and variability and how are they modulated by nutrient cycles? These questions represent the main barriers that prevent progress in assessing the ocean and land carbon sinks.

Question 2: What is the potential for amplification of climate change over the 21st century via biogeochemical processes and feedbacks?

Future climate change will be determined not only by anthropogenic emissions but also by the strength of the feedbacks between the physical climate system and the global carbon and nitrogen cycles. ESM projections now take some of these feedbacks into account. However, the C^4MIP activity highlighted how uncertain the magnitude of these feedbacks is. For instance, ESMs project that changes in climate and associated changes in ocean circulation and physical chemical buffering mechanisms will affect the ocean uptake of anthropogenic CO_2. How will this change the ocean's combined physical and biogeochemical capacity to sequester carbon? How will changes in temperature and precipitation patterns and intensity affect the exchanges of carbon between the atmosphere and the terrestrial biosphere? What is the net balance between climate change impact on plant photosynthesis vs. ecosystem respiration and other disturbances (such as fires)? Is there a risk for the terrestrial biosphere to become a source of carbon? Finally, what are the potentials of carbon-nutrient-water interactions and changes in atmospheric composition to influence land and ocean sources and sinks of carbon?

Question 3: How do GHG fluxes from highly vulnerable carbon reservoirs respond to changing climate (including climate extremes and abrupt changes)?

Many studies highlighted the potential for climate change to induce significant loss of carbon from vulnerable reservoirs. For example, a dieback of the Amazon forests induced by climate change has been suggested for decades, yet with inconclusive evidence. Similarly, warming at high latitudes leads to permafrost thawing with a risk of CO_2 and CH_4 release to the atmosphere. Further climate change also alters ecosystem disturbance regimes, which can significantly decrease carbon sinks and sporadically release CO_2 to the atmosphere. For the ocean, freshwater input to the North Atlantic, from melting of ice sheets and glaciers, has been suggested as a possible mechanism to could lead to a collapse of the oceanic thermohaline circulation with severe impacts on carbon uptake. Determining the impact of these processes (often referred to as "tipping points", "abrupt" or "irreversible" changes) on the climate system is of urgent interest, in particular to determine the level of climate change that could trigger these abrupt changes. However, in most cases, our science knowledge is not yet capable of quantifying the precise amount of carbon stored, the mechanisms involved in the loss of carbon, its vulnerability to climate change, or its potential recovery rate. We also remain unable to specify - or discount - clear physical or ecological thresholds in the climate system beyond which the vulnerability of these carbon reservoirs increases dramatically, and whether such thresholds are influenced not only by the amount but also by the rate of change.

3. The Research Initiatives

The overall effort to address the three guiding questions above will focus on specific advances in our understanding of biogeochemical processes that will lead to significant improvement in climate projections, with substantial progress expected in the next 5-10 years. This effort is divided into four research areas, addressing the three guiding questions and expected to progress in parallel. Experts will lead each research initiative; their task will be to stimulate and coordinate research activities within and to foster initiatives across the four research initiatives. The results from all the initiatives in this GC will be synthesized for broad dissemination using a consistent model framework and presentation in high quality publications.

R1: Process understanding on land (addresses Q1, Q2, and Q3)

Land ecosystems are currently responsible for removing about 25% of the anthropogenic CO_2 emissions. The land sink is the net balance between carbon flowing into terrestrial ecosystems through photosynthesis and carbon flowing out primarily through respiration processes and fires, but also via biogenic emissions to the atmosphere and leaching of carbon to aquatic systems. In addition, direct and widespread human interference on land through changes in land cover, crop and forest management, also has an impact on ecosystem mass balances and exchange. State-of-the-art Dynamic Global Vegetation Models (DGVMs) have improved representation of these carbon processes, accounting for the effect of changes in atmospheric CO_2, climate, nitrogen or ozone deposition and land use change. So far, however, DGVMs fail to show agreement in two highly policy-relevant scientific issues.

The first issue is the attribution of the main drivers for the current land carbon sinks at global and regional levels. It is known from atmospheric observations that, globally, the land is currently a net sink of carbon, but the respective roles of increased atmospheric CO_2, nutrient limitations, nutrient deposition from the atmosphere and direct inputs by human activities (fertilizers), ozone damage, climate change or land management are still under debate. Full attribution of the land sink to these potential drivers requires better representation of processes such as ecosystem response to CO_2, vegetation dynamics, ecosystem management, soil organic matter decomposition and disturbances sensitivity to climate. Current state-of-the-art DGVMs make necessary but over-simplistic assumptions. For example, they ignore long-term accumulation of carbon (e.g. in peatlands or permafrost) or long-term loss (e.g. carbon export to rivers), and poorly represent most disturbances (with the notable exception of fires), forest management, ecosystem acclimation, etc. In parallel to model developments, direct benchmarking against an increasing set of observations is needed. Evaluation of DGVMs against observations requires globally harmonized, definitive and accessible spatial and time-explicit datasets of basic carbon cycle quantities such as carbon stored in vegetation and soil, Gross Primary Production, Net Biome Production, and residence times of carbon in above- and below-ground pools.

The second issue, directly linked to the one above, relates to future projections. No major advancement has been achieved over the last 10 years regarding our understanding of land ecosystems responses to future climate change. Land carbon cycle sensitivities to increased CO_2

and climate change (sometimes referred as β and γ) show large uncertainties. Earth System Models still struggle to converge on future atmospheric CO_2 concentrations, and hence climate projections, when the models are directly forced by anthropogenic emissions. Significant progress will be achieved by more-coordinated efforts to isolate processes at play and to inter-compare and evaluate model responses, using existing or new manipulative experiments, such as enriched CO_2, soil warming or rain exclusion experiments.

Vulnerable land carbon pools are characterized by their quantity and a capacity for substantial change under 21st century climate change. Examples include, but are not limited to, carbon in tropical forest, wetlands, tropical or high-latitude peatlands and permafrost. Notably, most of these vulnerable carbon pools are poorly characterised or lacking in global datasets. While the tropical forest is characterized by a rapid turnover of carbon predominantly stored in biomass, peatlands, wetlands and permafrost ecosystems have accumulated large belowground carbon pools over longer time-scales. Research has highlighted the vulnerability of tropical forests, but modelling of some relevant processes remains rudimentary. In particular models generally overestimate the tropical forest sensitivity to droughts. In permafrost and peatlands, carbon accumulation due to anoxia and sub-zero temperatures in soils was not represented in CMIP5 ESMs. There is a general lack of realistic representation of the coupled soil physics and biogeochemistry system for these ecosystems. There is some model-based evidence that part of this carbon is vulnerable to release in the form of greenhouse gases under climatic changes but there is low confidence in the quantification of this feedback. The climate vulnerability of terrestrial carbon pools depends on multiple biogeochemical processes and feedbacks, of which only a few have been mentioned here. It is also evident that carbon uptake processes may be influenced and moderated by changes in atmospheric chemistry.

We propose to launch initiative R1 in a workshop dedicated to identifying key barriers in understanding the processes controlling land carbon uptake and assessment of vulnerable carbon pools. This workshop would generate a manuscript, with strong contributions from all relevant inter-disciplinary scientific communities, that outlines specific recommendations and realistic but challenging common research goals on a 5 to 10 year timeline.

R2: Process understanding in the ocean (addresses Q1, Q2, and Q3)

Absorbing about one-quarter of the emitted fossil fuel CO_2, the ocean has served as a major sink for the anthropogenic carbon during the industrial era. Recent advances in observations and ESMs shed light on the functioning of the ocean carbon sink. They confirm that increases in CO_2 emissions from fossil fuel burning are accompanied by an increase in carbon content of the upper ocean. Yet, by also revealing critical gaps in our understanding they drive increasing uncertainty of how ocean sinks will evolve in the future.

The overall global trajectory of CO_2 uptake by the oceans is consistently projected in current ESMs, reflecting long-term oceanic carbon uptake kinetics that is relatively well constrained. However, while the global ocean acts as a sink for anthropogenic carbon, different ocean regions currently in-gas (e.g. areas associated with deep water formation) or out-gas (e.g. the tropical ocean) CO_2 due to a combination of biogeochemical, thermal, and hydrodynamic conditions. Modern models are imperfect in representing these regimes of air-sea exchange of CO_2 in today's climate. Likewise, grasping their responses to natural climate variations and anthropogenic forcing remains challenging. The level of agreement among models is therefore lower on regional scales. For instance, the Southern Ocean accounting currently for >40% of the global ocean carbon sink is a clear flywheel of changes in atmospheric CO_2 but also a hot spot for uncertainties among modern ESMs. While CMIP5 ESMs project a continuous increase in the Southern Ocean carbon uptake, studies based on models driven by observations and atmospheric forcing from reanalysis suggest considerable variability over recent decades. This variability could partially be attributed to inter-annual oceanic and atmospheric dynamics (e.g. shifts in wind patterns over the Southern Ocean) and linked to inter-annual variability modes of the climate system that are not realistically captured in ESMs. Additionally, meso-scale eddies that are currently not resolved in ocean models may play a significant role in CO_2 uptake, by controlling open ocean biogeochemical cycles and productivity. Thus, the future of the ocean carbon uptake will be determined by the simultaneous changes in the atmospheric forcing and ocean circulation along with changes in biogeochemical processes. Because of the large content of carbon stored in the ocean, small changes in this reservoir can invoke large changes in atmospheric CO_2 concentration. Moreover, relatively slow timescales on ocean processes impede detection and attribution of changes in the ocean carbon cycle to natural variations or anthropogenic shifts. This complex nature of ocean carbon sink dynamics makes it a high priority in climate research. In particular, model and observational studies aiming at (i) constraining the natural variability of the ocean carbon sink and (ii) addressing the relationship between the uptake of excess heat and anthropogenic carbon are key in advancing this discipline.

Changes in marine ecosystems driven by climate change and increasing ocean carbon inventory (and associated ocean acidification) have the potential to strongly modulate the ocean carbon sink and climate feedbacks. Surface warming, increased stratification and reduced nutrient supplies to the upper ocean result in decreased oceanic primary production in ESM projections. In the Southern Ocean, however, enhancement of biological uptake of CO_2 in a warm future climate is projected. Furthermore, while the chemistry of ocean acidification associated with the dissociation of excess anthropogenic CO_2 in seawater is highly predictable in ESMs, the projected impacts on marine ecosystems are not straightforward, owing to insufficient process understanding as well as structural and parametric differences between the models. Biological sequestration of carbon is also affected by deoxygenation of the ocean interior in a more sluggish warm ocean. This process leads to the expansion of Oxygen Minimum Zones (OMZs) associated with poor ventilation and high biological consumption. The evolution of OMZs is driven by direct coupling between ocean dynamics and supply of oxygen, nutrients, and carbon to the upper ocean. The representation of these complex systems in modern ESMs is quite poor in space and time. As OMZs are sinks of biologically available nitrogen and sources of N_2O to the atmosphere, there is a strong need to improve their representation in projections of climate change. In summary, the response of marine ecosystems to the multiple stressors associated to climate change is not clear. Field-based process studies are imperative to improve model parameterizations and to address ecosystem and biogeochemical processes that are not well constrained in models.

Similar to R1, R2 will be launched with an interdisciplinary workshop intended to identify critical gaps in our understanding of the ocean carbon sink, the functioning of relevant marine biogeochemical processes and their relation to ocean physics. The outcome of the workshop will be a joint manuscript outlining common targets and proposed work plans in this field of research over the next 5-10 years.

R3: Learning from the existing record (primarily addresses Q1)

Existing records of components of the global carbon cycle have always been used in model development and evaluation. Annual updates of global and regional CO_2 budgets that extract information from the combination of data and model integrations will continue to play an important role in keeping track of the carbon pools evolution and provide an up-to-date understanding of the carbon cycle dynamics. As new data emerge and global coverage of existing data is continuously increasing (both in space and time), new opportunities emerge for comprehensive evaluation of many elements of the carbon cycle, including new information on the sensitivity of those components to climate change.

Satellite remote sensing of air column CO_2 concentration offers one good example of new emerging observational capabilities. While currently being more robust over land than over ocean, CO_2 satellite products are becoming available, potentially providing additional information over regions with very low surface network density. Continuous satellite CO_2 measurements could potentially provide new constraint on the temporal evolution and spatial distribution of land and ocean carbon sinks. Furthermore, deployment of profiling floats equipped with biogeochemical sensors, as proposed for SOCCOM in the Southern Ocean and beyond, promises a breakthrough in observing high frequency variability in physical and biogeochemical processes at the sea surface and in the ocean interior.

Over the recent years, new integrated data products have emerged from the scientific community such as GLOBALVIEW atmospheric CO_2, the Global Ocean Data Analysis Project (GLODAP), surface Ocean CO_2 Atlas (SOCAT), MODIS land surface datasets or the recent observation derived global flux datasets both for land and ocean CO_2 fluxes (FLUXCOM, SOCOM). In addition to these global products, there are numerous site-level datasets that could provide improved process understanding. Many other datasets are of potential interest for constraining the global carbon cycle such as atmospheric CO_2 isotopic composition or CO and CH_4 concentrations. Although model benchmarking is becoming more common in the ESM community, there is still a lack of consistent and transparent wall-to-wall evaluation (making use of all available datasets) of carbon cycle models as part of ESMs. Process oriented evaluation, such as assessing drivers-processes relationships, might also provide more information than a simple direct model-data spatial or temporal evaluation.

Ocean data products have recently emerged largely based on advanced mapping techniques and SOCAT observations. The data-products are being compared through the Surface Ocean CO_2 Mapping Intercomparison (SOCOM) project, which has identified an important potential for revealing quantitative estimates of regional oceanic CO_2 fluxes but with large differences, particularly in terms of variability. These methods have the potential to bring a step change in our ability to constrain the ocean CO_2 update on a year-to-year and multi-year basis.

Data assimilation techniques applied recently to the carbon cycle, such as CCDAS, also bring potential to provide model-derived datasets of quantities that are not currently observed. CCDAS is currently done in offline carbon cycle models. We could envision an ambitious exercise with CCDAS techniques being implemented in an Earth System reanalysis framework. ESMs could be used to provide a reanalysis of the climate and the carbon cycle as atmospheric and oceanic models of general circulation are currently used to provide atmosphere and ocean reanalysis.

The historical record is full of modes of variability in the climate system with clear impact on the carbon cycle. Evidences from long time series of atmospheric and oceanic measurements (interannual to decadal variability) as well as from the paleo record (glacial-interglacial, last millennium) show strong co-variances between climate and the carbon cycle; these have been used recently to infer the sensitivity of the global carbon cycle to climate change. The growing archive of interannual and decadal records of variability in GHG concentrations and surface fluxes provides a perfect opportunity to explore relationships between variability on different temporal scales. Recent studies on emerging constraints showed the potential use of observable changes in the carbon cycle (such as interannual variability). Such approaches should be extended to constrain future centennial sensitivity of numerous biogeochemical processes using observed, historical or paleo, time series (thereby also addressing Q2). In addition, decadal-scale memory in oceanic processes allows exploration of decadal predictability in the ocean carbon uptake. A detailed analysis of observational records should also allow identification of precursors of abrupt changes, their attribution to particular processes or signals in the mean state, and advances in the field of "early warning" signals in climate and carbon cycle change (thereby also addressing Q3).

R3 will address how provision of and access to new data (based on observational data products and process oriented observations), coupled with detailed analysis of modes of variability and process-oriented analysis of responses to drivers, will help to quantify and constrain carbon cycle feedbacks in ESMs. The challenge is to utilize this ever-growing data archive for (i) better attribution of changes in GHG fluxes to natural and anthropogenic processes and (ii) improvement of representation of biogeochemical processes in land and ocean models and hence in ESMs.

R4: Towards improved projections (addresses Q2 and Q3)

Earth system modeling aims at integrating our knowledge of the processes leading to interactions between biogeochemistry and climate. The field is currently in its infancy, with modelers facing the challenge of striking the right balance between representing a sufficiently wide range of relevant Earth system components and a sufficiently detailed description of the complex processes that occur within them. This initiative aims at improving the ESMs used for projecting future climate changes based on the work in the land, ocean and observation initiatives already described.

A key challenge will be to raise the profile of model development activities, particularly as it relates to improving parameterizations of biogeochemical processes in ESMs. These advancements must be based on our improved understanding of the physical, chemical and biological processes, and relationships between them, emerging from the outcomes of R1 and R2 and on comprehensive evaluation across scales within R3. The modeling community is currently on its way towards running full ESMs with higher spatial resolution, and higher coupling frequency between model components (i.e. AGCM and OGCM). Such model development is advantageous as it leads to a more comprehensive representation of the key physical and biogeochemical processes with their spatial and temporal variability. It also allows for a direct modeling of sub-grid processes, such as oceanic meso-scale eddies and atmospheric convection. A number of improvements should emerge from this progress. For instance, representation of meso-scale eddies which are thought to play a fundamental role in the Southern Ocean will provide a new insight on the estimates of the CO_2 uptake and the functioning of seasonal cycles in open ocean productivity. Likewise, improved representation of precipitation is key to model vegetation dynamics and soil moisture and thereby the land carbon cycle. Additionally, large ensemble simulations using ESMs will enable studies the range of natural (internal) variability and its role in regulating the ocean and land carbon sinks, and enable detection of anthropogenic changes.

Frameworks for feedback analysis have been recently developed. Biogeochemical climate feedbacks have been mapped on a common scale to physical climate feedbacks. Two key parameters quantify the sensitivity of carbon pools to changes in global burdens of atmospheric CO_2 (β), and the sensitivity of carbon pools to changes in global surface temperature (γ). Within this grand challenge the prospects for improving and potentially extending such frameworks will be explored. A particular focus will be on quantification of the carbon cycle response to regional forcing. This will include, for instance, the effect of changes in Amazonian precipitation on forest dieback and hence atmospheric CO_2 levels and radiative forcing, and the effect of regional deposition of nitrogen and ozone on global carbon sequestration. Processes contributing to non-linearity of the carbon cycle response to climate change will also be investigated. These include, for example, impacts of the weakening of ocean circulation and vertical mixing with climate change on oceanic carbon sequestration. This enhanced biogeochemical feedback framework and its quantified uncertainties will be combined with physical climate sensitivity to make improved projections of future climate change based on emission projections. This will allow us to refine the critical relationship between cumulative CO_2 emissions and surface temperature change with quantified lower and higher limits.

New challenges also emerge in terms of scenarios for future projections and their internal consistency. For example, the 1.5°C target recently discussed at the UNFCCC COP21 (Paris December 2015) would quite certainly require a large amount of bioenergy production combined with carbon capture and storage (BECCS), also known as negative emissions. ESMs need further developments to properly account for BECCS and their implications for land management and resources.

All together, a novel and crucial outcome of R4 of this grand challenge will be a coordinated effort toward improved projections of climate change. As for the previous research initiatives, we will propose a workshop later in the process with the objective to assess models improvements and their impact on historical and future projections of the coupled climate carbon cycle system. This activity will help reduce some major uncertainties on climate projections, as for example those associated with the Transient Climate Response to cumulative carbon Emissions (TCRE).

4. Opportunities for rapid progress

There are ongoing activities across the world that will ensure rapid progress tackling the four research initiatives of this GC. Owing to key activities such as CMIP and the contribution to IPCC assessments, the ESM research community is growing and is already well coordinated. For example, the CMIP activity included zero ESM in CMIP3, 11 in CMIP5, and about 20 are expected to contribute to CMIP6.

The CMIP6 project will coordinate several MIPs, providing a modeling framework for ESMs historical evaluation and future projections. In particular: relevant MIPs for the BGC-GC are the DECK and historical simulations for model evaluation of the land and ocean carbon uptake capacity; C^4MIP will provide crucial simulations for process understanding and BGC feedback quantification; and ScenarioMIP will provide future projections of carbon cycle under changing climate. In addition, OMIP, LS3MIP, and DCPP will provide additional process understanding of the physical drivers of biogeochemistry and modes of variability.

The growing observational network and products referenced in R3 will prove essential for process understanding, evaluation and improvement of ESM components. In particular, we will ensure close links with the major global scale dataset networks, such as SOCAT and GLODAP ocean CO_2 observations, AQUARIUS sea surface salinity, MODIS vegetation cover, GOSAT and OCO satellite CO_2, etc. The close connection with the annual CO_2 budget releases of the Global Carbon Project provides an ideal framework to regularly benchmark land and ocean carbon models and also to monitor their progress.

Model development and evaluation remain central to the BGC-GC. On-going international projects such as the EU/H2020 CRESCENDO focus on improvement and comprehensive evaluation of terrestrial and marine components of ESMs. ESMs have started, or will soon start, to include a more comprehensive representation of the nitrogen cycle both on land and in the ocean, of permafrost and wetland ecosystems, and exchanges across and processes within the land-ocean interface. In parallel, the dynamical cores of the ESMs are also being improved. Non-hydrostatic atmospheric models and high-resolution components are now being developed, allowing better small-scale physical dynamics with very positive impacts expected on biogeochemistry.

5. Implementation and coordination roadmap

We will establish a Biogeochemical Cycle Grand Challenge Steering Committee (SC) comprised of about 10 members who are worldwide leaders in the field. The SC will overview the implementation and progress of the four research initiatives listed above. A first task of the SC will be to associate each research initiative with clear objectives, work plans, and key individuals who will serve as leaders. All four research initiatives will be community-led activities.

The Grand Challenge will be launched in workshops to be held over the course of 2016-2019, involving small groups of leading experts on each of the research initiatives identified above. The objective of these workshops is to strengthen the links between the guiding questions and research initiatives as well as to emphasize major gaps and thereby sharpen the priorities and plans of the program as a whole. Our vision is to inspire and guide scientific communities on the overall problem of the Grand Challenge. Insights and outcomes of the workshops will be summarized in papers in high profile journals (e.g., Nature, Science or BAMS). As described above, we already envisage several workshops: (i) a Grand Challenge kick-off workshop to engage the community, refine and update the main research initiatives; (ii) two workshops focused separately on land and ocean processes; and (iii) a workshop on projections and feedback analysis. In addition we also envision some more specific workshops, as for example on Earth system model reanalysis.

This Grand Challenge will be supported by the WCRP Working Group on Coupled Modeling (WGCM). Collaboration with the other WCRP core projects (e.g. CliC, CLIVAR, GEWEX and SPARC) will be essential because of the importance of all elements of the climate system in controlling the biogeochemical cycles. Likewise, this Grand Challenge will benefit from close collaboration with Future Earth core projects (e.g. GCP, AIMES, SOLAS, ILEAPS). These groups could contribute coordination on particular initiatives within this Grand Challenge. The BGC grand challenge will also work in collaboration with other existing grand challenges. In particular, we already identified permafrost and feedbacks as a topic that will be addressed in collaboration with the GC-Cryosphere, with a joint workshop to be held in 2017.

Many aspects of the research initiatives of this GC are already being partly addressed through ongoing initiatives, such as the C^4MIP activity on coupled climate-carbon cycle modeling, the annual compilation and publication of the global carbon budgets by the GCP, the SOCAT program for surface ocean carbon observations, etc. Hence organizational effort will be not on starting many new initiatives, but rather on improving and providing important coordination, inspiration and intellectual leadership to help us collectively address the Grand Challenge's goals.