Proposal template
(technical annex)

Research and Innovation actions
Innovation actions

Title of Proposal

Coordinated **R**esearch in **E**arth **S**ystems and **C**limate**: E**xperiments**,** k**N**owledge**, D**issemination and **O**utreach

Project acronym

CRESCENDO

Horizon 2020 topic addressed

Advanced Earth-system models; SC5-01-2014

List of participants

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6	University of Exeter	UNEXE	UK
7	Deutsches Zentrum für Luft- und Raumfahrt	DLR	DE
8	Royal Netherlands Meteorological Institute	KNMI	NL
9	Norwegian Meteorological Institute	METNO	NO
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14	University of East Anglia	UEA	UK
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18	Ministry of Infrastructure and the Environment (PBL Netherlands Environmental Assessment Agency)	PBL	NL
19	Lund University	ULUND	SE
20	Potsdam Institute for Climate Impact Research	PIK	DE
21	Natural Environment Research Council (National Oceanography Centre)	NOC	UK
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1. Excellence

1.1 Objectives

CRESCENDO brings together 7 European Earth System Modelling (ESM) teams and 3 European Integrated Assessment Modelling groups, as well as experts in ESM evaluation methods, projection and feedback analysis, climate impacts, regional downscaling and science communication with the overarching aim to:

Improve the process realism and future climate projection reliability of European ESMs, while evaluating and documenting the performance quality of these models using a project-developed and openly-available community ESM evaluation tool (ESMValTool). Through the World Climate Research Program's (WCRP) 6th Coupled Model Intercomparison Project (CMIP6) CRESCENDO will contribute to the development of a new set of socio-economic/land use/emission scenarios and apply the project ESMs to these new data sets to generate an ensemble of ***novel*** *and* ***advanced*** *Earth system projections sampling a range of plausible future development pathways. These projections aim to deliver the most realistic estimate possible of the full Earth system response to future anthropogenic greenhouse gas emissions and land use change. By full Earth system we refer to* ***both*** *the physical climate response and interacting biogeochemical responses and feedbacks. Furthermore, through using ESMs that include representations of both the physical climate and key biogeochemical processes it becomes increasingly possible to assess interactively both Earth system change and a number of environmental responses to these changes which have important socio-economic or ecosystem impacts. Advanced analysis of biogeochemical processes and their climatic feedbacks will deliver an improved understanding of the reliability of these projections as well as isolating and quantifying the main Earth system feedbacks controlling both the magnitude and uncertainty of future climate conditions. Through this we will provide* ***robust*** *and* ***trustworthy*** *Earth system projection information to European researchers, policymakers and the public.*

Figure 1 shows the 7 ESMs and 3 IAMs involved in CRESCENDO, as well as the project partners involved in developing these models. Also shown are other project partners that are not directly linked to a single ESM. More details on the envisaged resolution of the ESMs to be applied in CRESCENDO and CMIP6 can be found in Table 1, section 1.1.4, page 8)

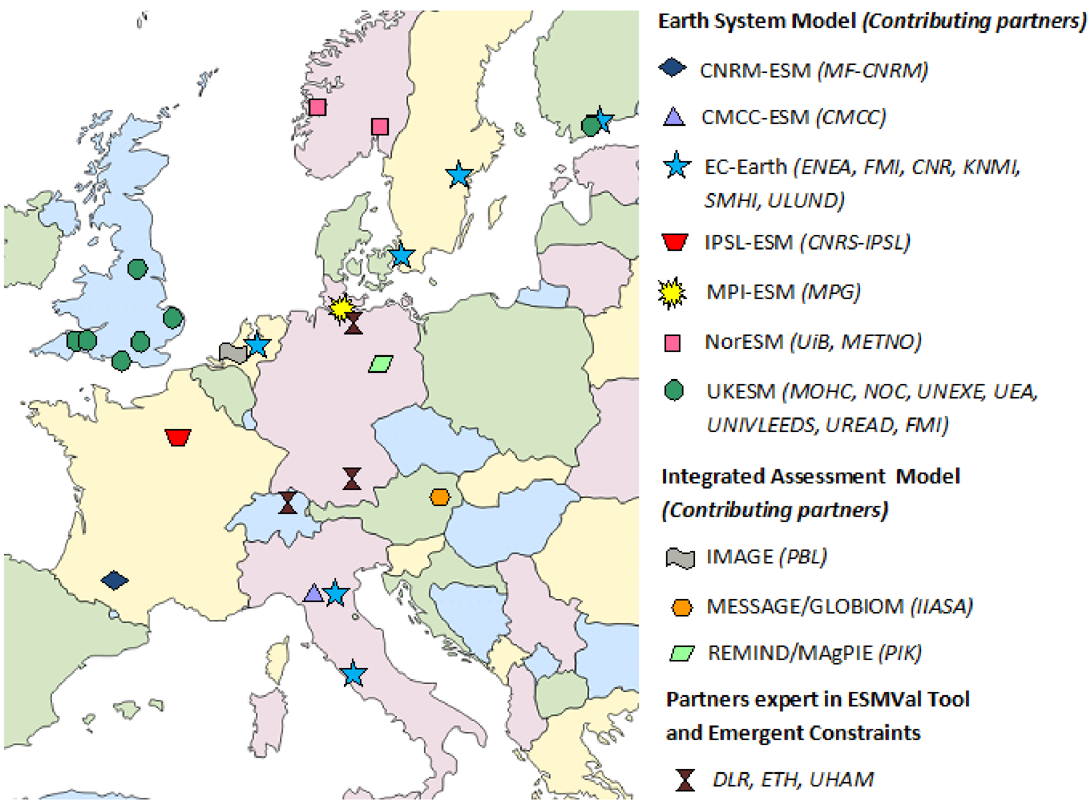

Figure 1: ESMs and IAMs participating in CRESCENDO along with the location of the partner model development groups and additional partners expert in ESM evaluation methods and emergent constraints.

The primary objectives of CRESCENDO are;

- To significantly improve the representation of key *biogeochemical, biogeophysical and aerosol* processes and feedbacks in seven European Earth System Models.
- To develop and apply a range of *process-level* evaluation methods to assess the realism of these newly developed Earth system processes in the project ESMs.
- To diagnose and categorize key Earth system biogeochemical and aerosol feedbacks and their associated radiative forcing using a common framework.
- To develop and apply advanced methods to quantify sources of uncertainty in Earth system projections and clearly document these uncertainties.
- To further advance the discipline of *emergent constraint* analysis, apply these techniques to ESM projections to constrain key future Earth system feedbacks and help focus model development onto processes crucial to the magnitude and spread of future Earth system change.
- To develop and apply, an openly-available, evaluation tool for routine ESM benchmarking and more advanced analysis of feedbacks and future projections.
- As part of the CMIP6 Scenario Model Intercomparison Project (ScenarioMIP), contribute to the development of a new set of policy-relevant future scenarios using the project IAMs.
- To deliver a coordinated ensemble of ESM projections based on new CMIP6/ScenarioMIP scenarios and ensure these data are saved on the Earth System Grid Federation (ESGF).
- To provide a coordinated set of simulations and advanced analyses to a range of CMIP6 *Model Intercomparison Projects (MIPs)* that align with the main project goals.
- To work with the climate impacts and regional downscaling communities to ensure ESM data produced in CRESCENDO is both useable and used in these complementary research areas.
- To ensure knowledge developed in the project is communicated to key stakeholder communities in an engaging and understandable form.

1.1.1 Improving key process parameterizations in European Earth system models.

Between IPCC AR4 (2007) and AR5 (2013) a number of physical Global Climate Models (GCMs) have been extended into Earth system models (ESMs), primarily through inclusion of an interactive treatment of the global carbon cycle (Cias et al. 2013; Box 6.4). This has allowed an assessment of the potential response of the Earth's carbon sources and sinks to **both** a changing climate and changing atmospheric concentrations of carbon dioxide (CO_2). Furthermore, ESMs are beginning to allow investigation of a range of important environmental responses to a warming climate and increasing CO_2 concentrations, some of which may feedback onto global climate change itself. Examples include; ocean acidification, and impacts on marine ecosystems and carbon uptake (Tagliabue et al., 2011); permafrost melt and it's socio-economic impacts and effects on methane/carbon release (Burke et al. 2013); wetland methane (CH_4) emissions (O'Connor et al. 2010) and changing wildfire risk and associated effects on land cover, carbon uptake and emission of chemical constituents (Ward et al. 2012) Furthermore, ESMs form a direct link between climate change and human activities, both near-term mitigation of aerosols, methane and black carbon and long-term emission targets require detailed knowledge of biogeochemical processes and feedbacks which only ESMs can provide. IPCC AR5 highlighted that a new set of *policy-relevant* questions can be addressed by ESMs, such as; the level of CO_2 emissions compatible with a given climate stabilization target or calculation of a new related climate change metric, *the transient climate response to cumulative carbon emissions* (TCRE, IPCC AR5 2013, Gillet et al. 2013). However, routine and coordinated assessment of ESM performance remains fairly limited and large uncertainty in ESM output hinders their productive use in decision making. With these factors in mind, CRESCENDO targets a systematic improvement and evaluation of the overall process realism of European ESMs to enhance confidence in their projections and increase the range of questions for which such model scan be reliably used.

Biogeochemical cycles in ESMs

Around 50% of the anthropogenic carbon emitted into the atmosphere is presently absorbed by natural sinks, split equally between the terrestrial and marine reservoirs (Le Quéré et al. 2013). The efficiency of these sinks is sensitive to the concentration of carbon in the atmosphere, the induced physical climate change (Arora et al. 2013) and the rate of CO_2 increase under different scenarios (Jones et al. 2013). Furthermore, carbon cycle sources and sinks are also sensitive to interactions with other nutrient cycles, such as nitrogen (Zaehle et al. 2011) and phosphorus over land (Goll et al. 2012) and the cycling of key nutrients through marine ecosystem processes (Steinacher et al., 2010). To accurately represent the global carbon cycle and its response to increasing CO_2 concentrations and induced climate change requires that ESMs include *realistic* representations of the interaction of key nutrient cycles (such as nitrogen and phosphorus) with the carbon cycle and with physical climate processes and variability. AR5 emphasized that ESMs indicate with *high confidence* that due to the response of the natural carbon cycle, a larger fraction of human-emitted CO_2 in the future will remain in the atmosphere than if the carbon cycle was unperturbed, *a positive carbon-climate feedback*. Uncertainty in the magnitude of this feedback remains significant (Friedlingstein et al. 2014) with the response of soil-vegetation processes, permafrost, wetland dynamics and marine biology being leading uncertainties at the process level.

While ESMs constitute a growing link between climate science and both the policy and impacts arenas, the reliability of their simulated response to anthropogenic forcing continues to be limited by problems in representing key physical climate and biogeochemical processes, as well as their responses to future anthropogenic drivers. To deliver more reliable estimates of future Earth system change an improved representation of *both* physical climate change *and* the interacting feedback response of key biogeochemical cycles are crucial to develop in the next generation of ESMs. A key goal of CRESCENDO is to *develop, implement and evaluate* a range of such process improvements in 7 European ESMs, addressing key terrestrial and marine biogeochemical phenomena.

Natural aerosols in ESMs

AR5 Working Group I states; *"uncertainties in aerosol forcing remain the dominant contributor to the overall uncertainty in net anthropogenic forcing"*, with *low scientific confidence* in the underlying processes. Carslaw et al. (2013) report that 45% of the variance in aerosol forcing since ~1750 arises from uncertainties in *natural* aerosol emissions, with only 34% of the variance due to anthropogenic emissions. Errors in the amount and/or representation of natural aerosols in ESMs have a significant impact on the pre-industrial aerosol state, against which the anthropogenic aerosol effect is generally diagnosed. Furthermore, natural aerosols directly interact with the anthropogenic aerosol field, with natural aerosol emissions themselves being sensitive to human-induced climate change (Carslaw et al. 2010). The radiative impact of anthropogenic emissions is therefore contingent on the amount, type and distribution of natural aerosols. Capturing such interactions in ESMs is important for an accurate estimate of both past and future total aerosol forcing.

It is anticipated that anthropogenic aerosol emissions will decrease in the future, meaning that in many parts of the world an understanding of natural aerosols will become increasingly important for understanding climate variability and long-term changes in the radiation budget. The majority of natural aerosol emissions involve interactions between the atmosphere and either marine or terrestrial biogeochemical processes (Carslaw et al. 2010, Six et al. 2013). Furthermore, reactive gases, emitted from wildfires, agriculture and the natural biosphere, influence natural aerosol processing through their impact on ozone, methane, secondary aerosol formation and the chemical composition of the atmosphere. To improve the simulation of aerosols in the Earth system it is necessary to improve *both* the treatment of natural aerosol and trace gas processes *and* their interaction with marine and terrestrial phenomena. This extends the demand on ESMs, beyond inclusion of solely marine and terrestrial biogeochemical cycles, to also include an advanced treatment of how atmospheric chemistry and aerosols interact with these systems. CRESCENDO will improve the treatment of natural aerosols in ESMs, ensuring realism in the underlying emission/deposition processes as well as in the atmospheric processing and activation of these aerosols. While we will not explicitly address the parameterization of cloud-radiation-precipitation in CRESCENDO, a critical determinant of the impact of aerosols on the radiation budget, we will ensure improvements made to natural aerosols in the project ESMs are well coupled to cloud-radiation developments in the component physical models through collaboration with scientists developing such schemes at each of the modelling centres.

1.1.2 Evaluating and analysing ESMs.

Process level evaluation of new parameterizations

A critical step in developing new process parameterizations and increasing confidence in ESM projections is to thoroughly evaluate the representation of these processes against observations. Evaluation of Earth system components has lagged behind that of physical climate processes, so developing process-based techniques to evaluate biogeochemical schemes is crucial for model improvement. The complexity of ESMs means improved parameterization must first be evaluated in a constrained model configuration, driven by observations (e.g. for a vegetation parameterization, running experiments with the land-only component of an ESM driven by observed atmospheric forcing). Targeted observations can then be used to evaluate the realism of the actual processes being simulated and assess the sensitivity of processes to a range of input variables defined from, and evaluated against, observations. Often referred to as *process-level* or *bottom-up* evaluation, CRESCENDO will develop a range of such methods to evaluate new ESM process descriptions focussing on; *terrestrial and marine biogeochemistry and natural aerosols*.

Full ESM evaluation and analysis

In addition to process-level evaluation, CRESCENDO will develop a community benchmarking system for evaluating coupled ESMs. Such a system, named *ESMValTool*, will benchmark key large-scale aspects of full ESM-simulated variability and trends, comparing to observations, earlier versions of the same ESM or different ESMs, as well as allowing assessment of key measures of Earth system change across a range of projection protocols. *ESMValTool* is already under development in the EU project, EMBRACE (http://www.embrace-project.eu), where a range of climate performance metrics and diagnostics are developed. In CRESCENDO we will extend this work to include additional biogeochemical and aerosol/trace gas metrics. The aforementioned process-level diagnostics will also be included in the *ESMValTool* source code repository, making them available to the wider research community. An important goal of *ESMValTool* is that it becomes a *community system*, open both to users and developers, encouraging open exchange of evaluation methods in order to avoid duplication of effort.

These two evaluation approaches, *bottom-up* (process-level) and *top-down* (full ESM benchmarking), aim to ensure ESMs deliver *the correct answer for the correct reasons*, while making sure overall realism in full ESM climate states is achieved. Both approaches are necessary to increase confidence in ESMs while retaining scientific rigour.

1.1.3 Emergent constraints to understand future projections and target model development

Model evaluation is a vital prerequisite for trustworthy climate projections to be used for policy guidance. However, evaluation often focuses on the accuracy with which a given model can simulate present-day spatial patterns of primary climate variables. There is an implicit assumption that models which accurately simulate these aspects of the current climate are most likely to deliver reliable projections of future climate, but this is not necessarily the case. This traditional approach to model evaluation does not necessarily consider the reliability of a given model for making future projections. Furthermore, the goal of achieving an accurate simulation of the present (observed) climate may be achieved by overly constraining model complexity/realism or through model tuning that introduces compensating errors at the process level. Such problems may ultimately *reduce* the reliability of ESM projections.

In CRESCENDO we address this problem by developing and applying the discipline of *emergent constraints* to a range of multi-model ensembles. An emergent constraint (Allen and Ingram 2002) refers to the use of observations to constrain a simulated future Earth system feedback. It is referred to as emergent, because a relationship between such a feedback and an observable element of climate variability emerges from an ensemble of ESM projections, providing a constraint on the future feedback. In the case of Cox et al. (2013) and Wenzel et al. (2014), an emergent linear relationship was established between the long-term sensitivity of tropical land carbon storage to climate warming and the short-term sensitivity of atmospheric CO_2 to inter-annual (ENSO-like) temperature variability. Such an emerging constraint offers the potential to reduce uncertainty in known feedbacks while helping focus model development on processes underpinning key projection uncertainties.

In CRESCENDO we will relate aspects of Earth system sensitivity to anthropogenic forcing, found to be common across an ensemble of ESMs, to observable aspects of Earth system variability. We will build on and advance the aforementioned efforts by; (i) better defining the theoretical basis for *emergent constraints* between short-term variability and long-term sensitivity in terms of the *Fluctuation-Dissipation Theorem* (Lucarini and Sarno 2011); (ii) deriving new emergent constraints targeting both physical and biogeochemical processes, (iii) developing and applying methods to quantify uncertainties in projections based on emergent constraints, taking into account model performance, model genealogical/structural interdependence and the existence of systematic model biases. The developed emergent constraints will also be implemented into *ESMValTool*.

1.1.4 Novel scenarios and policy relevant ESM projections: ScenarioMIP

The RCPs used in CMIP5 allowed a number of policy-relevant assessments to be made in AR5, providing an important link across the three IPCC working groups (*climate science, impacts-adaptation and mitigation*). However, the RCPs did not refer to a detailed description of the socio-economic pathways by which each RCP might be realized, nor did they span a plausible range of future emissions for aerosols and other short-lived species. Furthermore, some inconsistencies exist in the RCPs between climate, land-use and anthropogenic, as well as natural emissions. A number of these shortcomings are planned to be addressed in a new generation of scenarios (Van Vuuren et al., 2013) targeted for CMIP6 (Meehl et al. 2014). Referred to as ScenarioMIP, this effort brings together scientists from Integrated Assessment Modeling (IAM), Earth System Modeling, climate impacts-adaptation and mitigation research to develop a set of policy-relevant emission scenarios sampling a range of plausible future development pathways. These will form the basis for a new set of ESM projections in CMIP6. CRESCENDO IAM teams will contribute to the development of this new scenario set and ensure the resulting data is suitable for forcing ESMs.

To increase the utility of ESM projections for climate impact assessment, a sufficient number of simulations are required so a degree of statistical significance can be assigned, both to the simulated Earth system changes and to the resulting impacts. To address this CRESCENDO will generate an ensemble of multi-ESM, multi-member, multi-scenario projections using 2 different resolution versions of the project ESMs (with the lower resolution version being computationally faster). CRESCENDO groups will ensure at least 2-resolution versions of their ESMs are available during the project. The lower resolution, faster models will allow a more complete sampling of new scenarios with a large ensemble of simulations. To establish confidence in the resulting ensemble an acceptable level of performance and projection traceability between the 2 model versions will need to be established. Traceability across versions will be assessed using CMIP DECK simulations (*CMIP Diagnostic, Evaluation and Characterization of Klima experiments, see Meehl et. al 2014 for more details*) carried out with both model resolutions. Furthermore, a limited number of CMIP6 priority scenarios will be sampled both by the low and higher resolution model versions. Table 1 details the envisaged resolution of CRESCENDO ESMs. Combined with the IAM scenarios, the ESM ensemble of projections will constitute an important basis for research into Earth system change, climate change impacts, adaptation, vulnerability and mitigation.

Model	**High/Medium resolution models in CRESCENDO/CMIP6**		**Low resolution model for additional scenario runs in CRESCENDO**	
	Atmosphere	***Ocean***	***Atmosphere***	***Ocean***
CNRM-ESM	T127	0.25°	T127	1°
CMCC-ESM	1°	0.25°	1°	1°
EC-Earth	T255	1°	T159	1°
IPSL-ESM	1.3° x 0.65°	0.25°	2.5° x 1.25°	1°
MPI-ESM	T127/T63	0.4°/1.5°	T31	3°
NorESM	0.9° x 1.25°	0.25°	1.9° x 2.5°	2°
UKESM	0.65°	0.25°	1.5°	1°

Table 1: Envisaged resolution of ESMs for CRESCENDO simulations. Models referred to as low resolution are those likely used in CRESCENDO RT4 for generating an ensemble of projections based on the new CMIP6/ScenarioMIP scenarios. Some models may apply 3 different resolutions in CMIP6, these are indicated as high/medium/low in the table. Resolution is given in either degrees, grid point space or spectral wave number.

1.1.5 Knowledge dissemination and communication

The final challenge for CRESCENDO is to ensure dissemination and a broad uptake of the knowledge and data produced by the project. Dissemination will target a wide audience using methods that are both engaging and accurate. Dissemination platforms will range from peer-reviewed publications to public/policy-directed information sheets and targeted workshops. We will develop a public-facing online presence and, where suitable, use social media to get key information into the public-domain. We aim to explain the science behind Earth system modelling, how future Earth system projections are developed and analysed, as well as communicating robust future Earth system changes and the likely consequences of these changes. A further project aim is to train the next-generation of Earth system scientists to be capable and enthusiastic science communicators through provision of science communication training workshops. This will be carried out in collaboration with other EU projects, such as the FP7 HELIX *(High-End cLimate Impacts and eXtremes*) project, which shares the same dissemination team as CRESCENDO.

A key task will be to engage with other users of ESM data and knowledge, such as; *climate impact assessment and regional downscaling groups, as well adaptation and mitigation researchers.* CRESCENDO partners have extensive experience working with these groups and a sustained two-way interaction with key players in each area will be a priority. We will ensure simulations are fully accessible to the research community through the Earth System Grid Federation (ESGF). Partners have extensive experience in this activity through CMIP5. We already have an established collaboration with both the regional climate downscaling and climate impacts community, with project partners leading the WCRP CORDEX *(Coordinated Regional Downscaling EXperiment)* and ISI-MIP *(The Inter-Sectoral Impact Model Intercomparison Project)* projects. These partners will ensure a sustained collaboration between CRESCENDO and these disciplines, helping improve the knowledge and data chain delivering reliable Earth system change information for Europe.

1.1.6 Cross-cutting CRESCENDO activities contributing to CMIP6

CRESCENDO is structured to feed into and benefit from six *CMIP6 intercomparison projects (MIPs)*. Contributing to these MIPs through a single project will allow Europe to make a coordinated and significant contribution to CMIP6. CRESCENDO will also be able to draw on the expertise within the MIP communities to further enhance the development and understanding of the project ESMs. Here we outline the six MIPs, highlighting how each relates to CRESCENDO and indicate which CRESCENDO research theme (RT) is most linked to a given MIP.

ScenarioMIP: Scenario Model Intercomparison Project

ScenarioMIP brings together scientists from a range of Earth system science disciplines with the aim of; (i) defining and recommending an experimental design for future scenarios to be run by climate models as part of CMIP6, (ii) coordinate the provision of IAM scenario information to climate modelling groups, and (iii) coordinate the production of ESM simulations and facilitate provision of output. CRESCENDO scientists are already involved in ScenarioMIP and throughout the project will contribute to the above aims. The 3 project IAM teams will contribute to development of the underlying socio-economic scenarios (RT4), while the 7 project-ESMs will use these scenarios to generate an ensemble of new projections based on these projections (RT4). C^4MIP, LUMIP and AerChemMIP (described below) collaborate with ScenarioMIP addressing respectively; (i)climate change feedbacks involving the terrestrial and marine carbon cycles, (ii) climate change effects of future de- and af- forestation scenarios, combined with the mitigation potential of land use and land cover changes (LUMIP) (RT1 and RT3) and (ii) exploring future uncertainties in aerosol and trace gas emissions and their impact of Earth system change (AerChemMIP) (RT3, RT4).

C^4MIP: The Coupled Carbon Cycle Climate Model Intercomparison Project

C^4MIP is the main international collaboration investigating coupled carbon cycle – climate feedbacks in ESMs (Friedlingstein et al. 2006). As in CMIP5, 3 sets of simulations will be performed in C^4MIP using updated CMIP6 ESMs; (i) fully coupled simulations (1%/year CO_2 increase as part of the CMIP DECK); (ii) biogeochemically active simulations, where atmospheric CO_2 increase has no radiative effect, and conversely (iii) radiatively active simulations, where atmospheric CO_2 increase has no direct effect on land or ocean biogeochemistry. These simulations allow quantification of two key ESM characteristics; (i) the sensitivity of biogeochemical cycles to changing atmospheric CO_2 (*the concentration-carbon feedback*) and (ii) the sensitivity of biogeochemical cycles to a changing climate (*the climate-carbon feedback*). CRESCENDO will carry out these calculations using project

ESMs, considering the majority of processes targeted for improvement, including; the carbon cycle (with nitrogen limitation), CH_4 emissions from wetlands and permafrost, nitrous oxide (N_2O) soil emissions, wildfire emissions, dimethylsulfide (DMS) and biogenic volatile organic compounds (BVOC) emissions and fluxes of mineral dust and sea salt. C^4MIP simulations will be used to investigate emergent constraints on biogeochemical cycle–climate feedbacks (RT3), for evaluating simulated carbon cycle–climate interactions (RT1 and RT3) and for diagnosing the radiative forcing associated with carbon cycle feedbacks (RT3).

LUMIP: Land Use Model Intercomparison Project

Human land-use has led to large changes in the Earth's surface, with implications for climate. In the future land-use activities are likely to expand to meet growing societal demands. Improved understanding of the role of land use and land cover changes (LULCC) in the climate system is urgently required (Brovkin et al. 2013). CRESCENDO will ensure project ESMs use a common (and documented) method to translate LULCC scenarios to the land surface types used in the models and that biogeochemical and biophysical fluxes related to land use are calculated and evaluated consistently across ESMs. We aim to reduce uncertainties in the response of climate and carbon sources/sinks to past and future LULCC changes. LUMIP simulations proposed for CMIP6 include (i) idealized experiments with gradual global deforestation per year (to complete deforestation) to quantify ESM sensitivity to forest; (ii) historical simulation without LULCC to complement the CMIP DECK simulation with LULCC; (iii) in coordination with ScenarioMIP, two future projections with minimum and maximum deforestation scenarios to quantify the mitigation potential of LULCC. CRESCENDO will play an active role in specifying these simulations, will ensure project ESMs make a coordinated contribution and take a lead role in analysing model results. LUMIP activities in CRESCENDO occur primarily in RT1, RT2 and RT4.

LS3MIP: Land Surface, Snow and Soil Moisture Model Intercomparison Project

The new Land Surface, Snow and Soil Moisture Model Intercomparison Project (LS3MIP) builds upon several past MIPs investigating biogeophysical feedbacks from land processes on climate. A core element of this project is the follow-up of the Global Land-Atmosphere Coupling Experiment (GLACE), a multi-phase project coordinated by the Global Energy and Water Exchange Project (GEWEX), investigating impacts of land hydrology on climate (including vegetation-mediated effects). The GLACE-Coupled MIP Phase 5 (GLACE-CMIP5) ran using CMIP5 projections (Seneviratne et al. 2013). Experiments consisted of historical and scenario runs modified from the CMIP5 standard by soil moisture and snow cover being prescribed either to a transient climatology or values from a reference period (e.g. late 20th century). In CRESCENDO, the GLACE component of LS3MIP will be run by participating models as well as expanded to focus on interactions between projected changes in *drought occurrence and biogeochemical/carbon cycle and LULCC feedbacks* on climate (in coordination with C^4MIP and LUMIP). The overall set of experiments (LS3MIP/GLACE-CMIP) will enable the identification of emergent constraints associated with water-related biogeochemical/carbon cycle and LULCC feedbacks (RT3). Uncertainties in the forcing associated with LULCC have been shown, to a large extent, to be conditioned by soil moisture impacts on land hydrological fluxes for different land use and cover categories, this interaction will be analysed jointly in LS3MIP/GLACE-CMIP and LUMIP (RT1, RT2, RT4). Similarly the key role played by land-surface hydrology in the terrestrial carbon cycle response to climate change will be jointly analysed through C^4MIP and LS3MIP/GLACE-CMIP (RT1 and RT3).

AerChemMIP: Aerosol and Chemistry Model Intercomparison Project

AerChemMIP is a subproject of two initiatives; AeroCom (*Aerosol Comparisons between Observations and Models*) and CCMI (*Chemistry-Climate Model Initiative*) and aims to further advance our ability to simulate and diagnose chemistry-aerosol processes. CRESCENDO contributes to and expands AerChemMIP by improving and evaluating natural aerosol and ozone precursor processes in the project ESMs and performing experiments to diagnose natural and anthropogenic radiative forcing and feedbacks. The latter will investigate the impact of an improved treatment of natural aerosols and, by association, a changed pre-industrial aerosol state (Carslaw et al. 2013) on estimates of anthropogenic aerosol forcing over the historical period. This will be achieved through a suite of simulations parallel to the CMIP DECK runs that iteratively allow different components of the full aerosol-radiation effect to be activated in the ESMs (RT3). Diagnostics will be developed allowing analysis of all relevant effective radiative forcings, as well a consistent quantification of fast and slow feedbacks involving aerosols and reactive gases following the methodology of Gregory et al. (2009) and Collins et al. (manuscript in preparation) (RT1 and RT3).

OCMIP6: Ocean Carbon Cycle Model Intercomparison Project

OCMIP6 will parallel the coupled CMIP DECK historical simulations run by CRESCENDO models. In coordination with the CORE (*Coordinated Ocean-Ice Reference Experiments*) group, OCMIP6 will develop an experiment protocol whereby ocean dynamical-biogeochemical models used in coupled ESMs are run in stand-alone mode, driven by observation-based forcing. These simulations will investigate the benefits of improved ocean model resolution and process description, in moving from CMIP5 (typical ocean model resolution of ~1-2°) to CRESCENDO/CMIP6 (typical ocean model resolution of ~0.25°, (*eddy-permitting)*), on simulated marine biogeochemical cycles, particularly carbon uptake. Increased model resolution implies partial resolution of shelf and coastal seas, providing an opportunity to investigate the ability of models to represent shelf-sea/coastal dynamical-biogeochemical processes and exchanges with the deep ocean, as well as the influence of riverine carbon fluxes and their sensitivity to future global change (RT1 and RT2).

1.2 Relation to the work programme

CRESCENDO addresses the Horizon 2020 call: **H2020-SC5-2014; Advanced Earth-system models.** With reference to the call text we detail how CRESCENDO address a number of key goals of this call:

Proposals should develop a new generation of advanced and well-evaluated global climate and Earth-system models as well as sophisticated climate related prediction systems with the aim of providing to governments, business and society in general state-of-the-art trustworthy scientific input to climate risk assessments

We include all seven European ESMs in a one project to ensure shared improvement of models across Europe and enhance coordination for CMIP6. This will ensure maximum efficiency in generating an ensemble of Earth system simulations for use both *within* and *external* to the project. We target improvement of ESM processes known to be deficient or absent in current models, that are also leading contributors to the magnitude and uncertainty of Earth system projections, these include; (i) terrestrial carbon cycle processes and other nutrient cycles (e.g. nitrogen) impacting carbon uptake under climate change, (ii) marine biogeochemical processes influencing marine carbon uptake and air-sea fluxes of N_2O and (iii) natural aerosol processes and interactions with atmospheric chemistry and the radiation budget. Emphasis will also be placed on interactions across these three domains, as well as with the physical climate.

We will move ESM evaluation beyond the state-of-the-art by investing in operational benchmarking of *physical* and *biogeochemical* aspects of ESMs, process-oriented evaluation and by identifying processes most important to the magnitude and uncertainty of future projections. Process evaluation will target new parameterizations developed in the project and aims to ensure ESMs get the correct results for the correct reasons. The project will develop and apply a community-wide Earth System Model Validation Tool (ESMValTool) that can be used to benchmark ESM performance against other ESMs and against suitable observations (e.g. Obs4MIP (*Observations for model intercomparison projects*), ESA Climate Change Initiative (CCI) or synthesized in CRESCENDO). The ability to routinely perform such comprehensive evaluation, combined with process-oriented evaluation, will drive the quality and realism of ESMs forward. ESMValTool will provide a documentation function in CMIP to help understand systematic model errors in the ongoing CMIP Diagnostic, Evaluation and Characterization of Klima (CMIP DECK) experiments (Meehl et al. 2014).

These developments will result in an ensemble of advanced and well-evaluated ESMs capable of providing state-of-the-art, trustworthy projection information while retaining diversity in scientific approach.

Relevant physical, chemical and biological Earth-system processes, including anthropogenic drivers as well as socio-economic aspects and their feedback need to be adequately incorporated into climate models predictions and projections at the appropriate scale

CRESCENDO emphasizes enhancing the realism and accuracy of ESMs through targeted improvement of existing and/or introduction of new Earth system processes. New developments include: *(i) A more complete treatment of the nitrogen cycle and its coupling to the global carbon cycle. (ii) Permafrost and wetland processes, including CO_2 and CH_4 emissions and their chemical and radiative treatment. (iii) Wildfires and impacts on atmospheric composition, land cover and carbon stocks. (iv) A consistent definition of land use/land cover changes in ESMs. (v) Terrestrial emissions of biogenic trace gases and impact on aerosols and radiation. (vi) Marine emissions of DMS, bio-aerosols and sea salt. (vii) Mineral dust emissions, marine iron deposition and* *ocean productivity. (viii) Improved small scale ocean circulation/mixing and interaction with marine biogeochemistry. (ix) Marine phytoplankton production, phenology and export efficiency. (x) Representation of shelf-sea and coastal processes.* We will develop and apply methods to evaluate the realism of these process descriptions and quantify their role in future projections. We will also focus on the development of new socio-economic scenarios for ESMs that will be designed to maximize utility in a broad range of science to policy disciplines. We will ensure project ESMs use these scenarios to generate a coordinated ensemble of Earth system projections and that this data is made openly available through the ESGF.

Key outcomes of the project will include; a set of more realistic and evaluated European ESMs, new emission scenarios for driving ESMs, as well as a multi-scenario/ESM/member set of projections based on these new scenarios. Projections will be available for scientific analysis and use in climate change impact assessment (ISI-MIP), as well as for driving regional climate models (external to CRESCENDO, e.g. in WCRP CORDEX).

New methods for representing uncertainties in Earth-system models should help to assess the reliability of regional responses and their impacts on key economic sectors

CRESCENDO will further develop and apply the discipline of *emergent constraints* to deliver observationally constrained estimates of key future Earth system feedbacks. Emergent constraints will provide a better estimate of the sensitivity of the Earth system and a new set of projection-relevant metrics against which ESMs can be assessed. They also offer a means to focus future model development and evaluation on aspects of the current climate that relate strongly to future projections. We will also develop improved methodologies for combining multi-model/multi-member ESM ensembles, taking better account of aspects such as model interdependencies, shared model genealogy and the existence of common systematic biases across models. The aim is to provide a more robust and accurate estimate of ensemble projection uncertainties.

CRESCENDO includes partners who lead major international projects in climate impact assessment (*ISI-MIP and the FP7 HELIX project*) and regional climate downscaling (*WCRP CORDEX*). Through engagement with these communities we will ensure CRESCENDO data is disseminated in a supported manner for use in assessing climate change impacts. Sustained collaboration between CRESCENDO and these communities will be to the benefit of all 3 disciplines and to the provision of actionable Earth system change information.

Advanced high resolution Earth-system models should provide the basis for producing novel climate scenarios

As mentioned earlier, the RCPs used in CMIP5 allowed a number of policy relevant conclusions to be drawn but, they did not include an explicit description of the underlying socio-economic conditions and, therefore, their use for assessment of impact, mitigation and adaptation costs were limited. In ScenarioMIP a more integrated approach to combining socio-economic and climate scenarios is aimed for. Different communities will formulate a more explicit description of how new ESM simulations fit into the overall framework of future socio-economic and climate change. Scenarios will address temporally and regionally specific aspects related to ozone, methane, N_2O and aerosols, as well as land use change. CRESCENDO will take a lead role in both the development of these new scenarios and their subsequent use in generating ESM projections.

CRESCENDO aims to use a set of traceable, lower resolution versions of the project ESMs to generate an ensemble of future projections that samples a range of the new CMIP6 scenarios, including both ScenarioMIP recommended projections and other relevant community scenarios *(sampling scenario uncertainty),* using multiple ESM realizations *(sampling model uncertainty)* and multiple realizations of each ESM for a given scenario *(sampling initial condition uncertainty)* in order to span the combined uncertainty space of future projections (e.g. Hawkins and Sutton 2009). The computational cost associated with such an undertaking likely necessitates the use of lower resolution (computationally fast) ESMs in combination with more standard-resolution CMIP6 models. These will be based on the standard (higher resolution) CMIP6 ESMs, with similar levels of process complexity, but resolutions more similar to those in CMIP5, allowing a significantly larger number of projections to be made. We will document the traceability of these lower resolution models against their higher resolution equivalents to increase confidence in the resulting projection ensemble, with a limited number of scenarios sampled by both standard and low resolution versions of some ESMs.

Future models should have the capability of better understanding past climatic variability and its causes and impacts (societies, resources and ecosystems) as well as recent climate records.

We will use ESMValTool applied to the pre-industrial and historical periods of the CMIP DECK runs to assess whether ESMs are able to capture past inter-annual to multi-decadal Earth system variability, in the physical climate, as well as in biogeochemical cycles and natural aerosols. Improvement and inclusion of a more advanced treatment of biogeochemical processes opens up a range of new observational opportunities to evaluate such models. Furthermore, an emphasis on improved representation of natural aerosols may have a significant impact of the pre-industrial aerosol state with implications for model estimates of the anthropogenic aerosol forcing. CRESCENDO will develop model capabilities beyond CMIP6. We therefore do not envisage all new process parameterizations will be fully implemented and tested in the coupled ESMs by the conclusion of the project. Hence, analysis of long-timescale Earth system variability in these improved models will be carried out by partners *after* the conclusion of the project, extending the impact of CRESCENDO well beyond its formal conclusion.

1.3 Concept and approach

CRESCENDO combines an ensemble of ESMs and IAMs with advanced analysis methods to improve key ESM process-parameterizations while also *producing, understanding, constraining and quantifying* an ensemble of ESM projections. These activities necessarily occur in parallel, with new projections using mature ESMs in the 1st half of the project (e.g. CMIP6-standard models) and process improvements being developed and implemented into these ESMs throughout the project, resulting in an improved set of European ESMs at the conclusion of both CRESCENDO and CMIP6.

CRESCENDO includes 7 European ESMs and, by association, the main European ESM development institutes. As well as contributing to extensive development of these world-leading models, several activities in the project will significantly leverage wider modelling efforts at these centres, particularly with respect to coupling Earth system parameterizations and physical component models. We have therefore worked to ensure CRESCENDO is seen as a central *model development, evaluation and application effort* at all participating centres over the lifetime of CMIP6. CRESCENDO modellers generally work in the same institute or even group as physical component model developers, regular interaction is ensured, increasing the likelihood project activities will impact long-term ESM development in Europe.

CRESCENDO is structured into 5 Research Themes (RTs, see figure 2), plus a project management work package (WP6, not shown in figure 2). Each RT addresses a science or dissemination goal of the project. RTs are further divided into a number of work packages (WPs) allowing increased research focus. CRESCENDO is structured to feed into, and benefit from, six CMIP6 Model Intercomparison Projects (MIPs). These are key cross-cutting project activities. In particular, CRESCENDO is the main European contribution to the generation of new scenarios and ESM projection data in CMIP6/ScenarioMIP. Figure 2 also shows the central role of the CMIP DECK simulations made with the partner ESMs using their standard resolution CMIP6 ESMs. These formally occur outside the project, carried out by the individual centres themselves. All centres will ensure these CMIP DECK runs are fully available midway through the project. Figure 2 highlights the importance of **RT5:** *Knowledge and data dissemination*. All RTs will provide regular input to RT5 to maximize the quality and timeliness of knowledge dissemination from the project

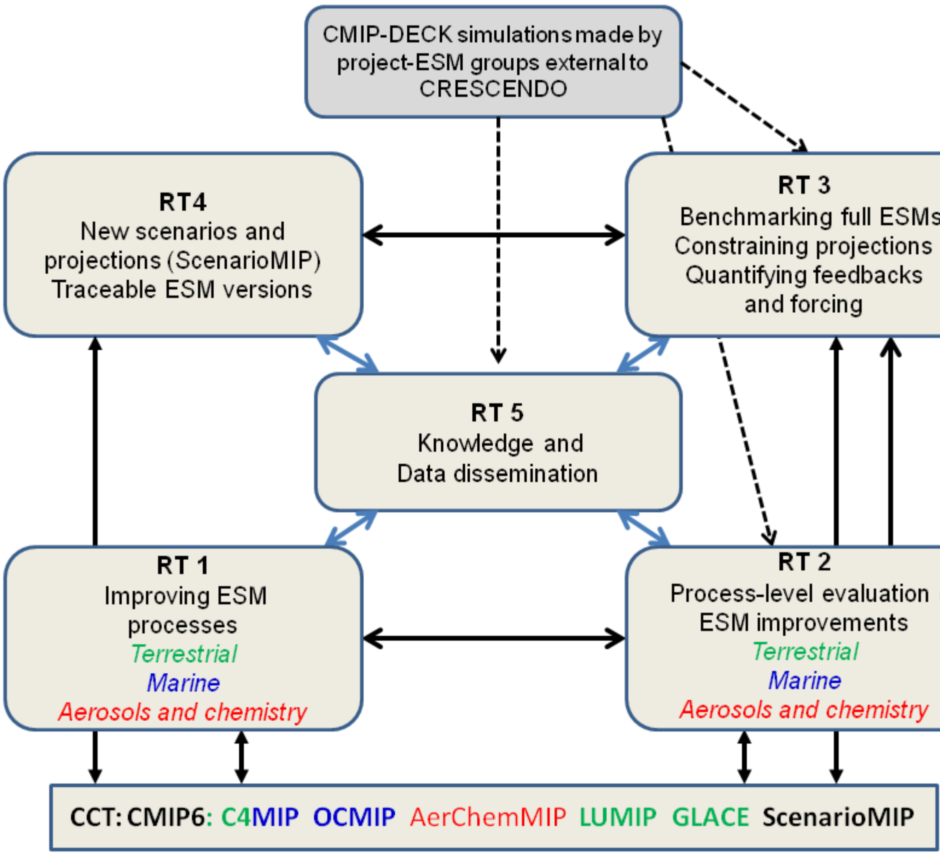

Figure 2: Research Themes (RTs) and Cross-Cutting Themes (CCTs) in CRESCENDO. Colours indicate which of the 3 domains; terrestrial, marine, or aerosol-chemistry; the various MIPs primarily contribute to.

RT1 focuses on improving the process realism of ESMs while **RT2** is the evaluation equivalent of RT1, with each process area in RT1 having a process-level evaluation task in RT2. There will be a tight and continuous interaction between RT1 and RT2, with regular exchange of model simulations and evaluation results between the two RTs in order to drive forwards model improvement. **RT3** focuses on evaluating fully-coupled ESMs, both for the observed past (*performance benchmarking*) and for future projections. RT3 is also where the ESMValTool will be further developed to include performance metrics for key Earth system phenomena in addition to existing physical climate metrics. RT3 will also develop a set of emergent constraints using projections made in the CMIP DECK and ScenarioMIP. Finally RT3 will quantify key Earth system feedbacks using a common framework based on effective radiative forcing efficiencies. **RT4** focuses on the design of new socio-economic scenarios as part of ScenarioMIP, as well as applying the project ESMs to these scenarios. **RT5** emphasizes two primary dissemination foci; (i) saving CRESCENDO data to the ESGF, with supported use of this data in climate impacts (ISI-MIP) and regional climate downscaling (CORDEX); (ii) delivery of accessible knowledge to a range of audiences on the science of Earth system modelling, projections and the use of projections in impact assessment, adaptation and mitigation. **WP6** is responsible for overall coordination and day to day running of the project. More detail on project management is provided in section 3.2.

1.4 Ambition

1.4.1 Improving ESM process realism and reliability: Terrestrial Biogeochemical Processes

Analysis of CMIP5 reveal a number of key processes poorly represented in current terrestrial models; these include (a) the role of nitrogen in limiting ecosystem productivity, (b) emission of methane from wetlands and permafrost and (c) the role of land use, land cover change and wildfires in the climate system (Ciais et al., 2013).

Interaction between carbon and nitrogen cycles reduces the terrestrial carbon uptake in response to increased atmospheric CO_2 due to nitrogen limitation on photosynthesis, but also reduces carbon loss in response to warming through enhanced nitrogen remineralisation. Anthropogenic nitrogen deposition also has important consequences for carbon sequestration and hence, indirectly for climate (Zaehle and Dalmonech 2011). The terrestrial nitrogen cycle therefore, acts both as a forcing and feedback for the terrestrial carbon cycle. AR5 assessed with *high confidence* that low nitrogen availability will limit carbon storage on land in the future. Omission of the nitrogen cycle in models is thought to lead to an overestimation of ~100-200 PgC in terrestrial carbon uptake by 2100 (Zhang et al. 2014). Inclusion of nitrogen cycle processes in ESMs, combined with a thorough evaluation, is therefore crucial to move beyond the state of the art. CRESCENDO will develop coupled carbon-nitrogen cycle models for the project ESMs, accounting for plant uptake of nitrogen, atmospheric deposition, soil nitrogen remineralisation and NO_x and N_2O emissions from soils. We will also develop advanced performance metrics to test these improvements.

AR5 assessed "it is *virtually certain* near-surface permafrost extent at high latitudes will be reduced as global mean surface temperature increases". AR5 also concluded there is *low confidence* in the amount of CO_2 or CH_4 released to the atmosphere from thawing permafrost, varying by a factor of five (50 to 250 GtC loss by 2100) for RCP8.5. Sources of uncertainty include; physical thawing rates, the fraction of carbon released after thaw and the time scales of release. It is also uncertain how much thawed carbon will decompose to CO_2 or to CH_4. There is only *medium confidence* that emissions of CH_4 from wetlands are *likely* to increase in the future with *low confidence* in quantitative projections. Both thawing of permafrost and existing wetlands have the potential to increase emissions of CH_4 in the future. AR5 indicates *high uncertainty* and *low confidence* in these model processes (Ciais et al., 2013). CRESCENDO will improve the treatment of permafrost and wetland dynamics as well as CH_4 and CO_2 in atmospheric components of ESMs, evaluate these process improvements in RT2 and develop metrics of performance for coupled ESMs in RT3.

Less than half of CMIP5 ESMs included fire modules and detailed analysis of fire projections and fire module evaluation remains quite limited. Development of fire modules in ESMs is a high priority as fires can impact on land cover, the terrestrial carbon sink, atmospheric composition and have major socio-economic consequences. In CRESCENDO we will introduce a robust set of fire modules into the project ESMs and evaluate their performance both at the process and full-ESM level. We will also investigate possible constraints on future fire risk related to key aspects of climate variability and analyse the risks for changed fire occurrence in ESM projections.

For the first time, CMIP5 ESMs included Land Use and Land Cover Changes (LULCC) as an external forcing of both the physical climate and carbon cycle. However, large differences across models in the implementation of LULCC limited the value of the CMIP5 results; with additional simulations showing large uncertainty in the amount of carbon loss following deforestation (Brovkin et al., 2013). CRESCENDO will develop an improved and common LULCC representation in ESMs, along with evaluation techniques, and an experiment design to ensure CMIP6 experiments provide more useable (science and mitigation) information. Most ESMs treat forests as natural, undisturbed ecosystems, neglecting the potential effect of forest management on carbon uptake. CRESCENDO models will introduce age or size classes in forest ecosystems to better simulate the dynamic of managed forests.

1.4.2 Improving ESM process realism and reliability: Marine Biogeochemical processes

CMIP5 ocean models exhibit significant biases in key physical circulation features and biogeochemical processes (Ciais et al. 2013). Specific improvements required include (a) Equatorial and coastal upwelling and cross-boundary exchanges, such as between coastal shelves and the deep ocean; (b) inclusion of external nutrient inputs to the ocean (via atmospheric deposition and rivers); (c) accurate representation of oxygen minimum zones (OMZs); (d) more advanced ecosystem-specific formulations of biogeochemistry; (e) improved fluxes of non-CO_2 trace gases and aerosol precursors. CRESCENDO partners are at the forefront of research in these areas (e.g. Bopp et al. 2013; Séférian 2013; Suntharalingam et al. 2012; Six et al. 2013). We will develop a range of new process parameterizations and model configurations to address the issues above, providing a step-change in ocean model capabilities for the next generation of ESMs, these developments include:

Improvements in physical circulation through higher spatial resolution: CMIP5 ocean models typically have horizontal resolutions of ~1-2° and relatively poor representation of; deep winter convection, water mass formation, equatorial upwelling, and ocean stratification (Danabasoglu et al., 2014, Sallée et al., 2013). In CRESCENDO we will employ eddy-permitting ocean models (~0.25° resolution), with advanced sub-grid scale mixing parameterizations, as part of fully coupled ESMs. We envisage major improvements in key circulation features, and as a result, improvement of marine biogeochemistry. Coastal processes and ocean-shelf exchanges are poorly represented in CMIP5 models, but may play a significant role in the global carbon budget (Regnier et al. 2013). Coastal areas are also the most affected by anthropogenic nutrients (Seitzinger et al.2010). In CRESCENDO higher ocean model resolution will allow partial resolution of shelf-sea processes and for the first time, land-ocean, as well as shelf to deep ocean fluxes can be addressed within an ESM framework

External nutrient inputs to the ocean: AR5 highlights the potential importance of external nutrient inputs to the ocean (e.g. nitrogen fluxes from the atmosphere and rivers, and inputs of iron from desert dust). Off-line ocean models suggest substantial impact of these on ocean biogeochemistry and trace-gas fluxes (Krishnamurthy et al. 2009; Suntharalingam et al. 2012). AR5 report *low confidence* in current estimates of reactive nitrogen deposition in remote ocean regions. Uncertainty also exists in the distribution of dust deposition over the open ocean, and its impact on ocean biogeochemistry. In CRESCENDO we will incorporate such nutrient fluxes into ESMs, evaluate their impacts on ocean biogeochemistry, and assess the potential for major feedbacks.

Ocean oxygen depletion: Ocean dissolved oxygen has decreased over the 20th century with further decreases projected for the 21st century, with consequences for marine organisms and biogeochemistry (Stramma et al., 2010). The extent and intensity of sub-oxic and hypoxic ocean zones are important determinants of the marine nitrogen cycle and the production and destruction of N_2O. CMIP5 models exhibit a poor representation of OMZs (Andrews et al. 2013) due to poor resolution of equatorial current systems and inaccurate ventilation of tropical water-masses (Stramma et al. 2012). In CRESCENDO, through higher resolution, we anticipate improvement in the representation of these features and in the extent of OMZs.

Organic matter cycles: CMIP5 models use simple parameterizations of key biogeochemical processes (e.g., NPZD models, fixed elemental ratios for the formation of organic matter, fixed lability for dissolved organic matter, Bopp et al. 2013). Such formulations may be inadequate, with implications for ocean model estimates of CO_2 uptake (Weber and Deutsch, 2010). We will improve the "*flexibility*" of these parameterisations through inclusion of variable nutrient ratios for organic matter production as a function of ecosystem change, improved representation of remineralization processes, and variable lability for dissolved organic matter.

Representation of trace-gas fluxes: Changes in ocean-atmosphere fluxes of radiatively-important trace-gases and aerosol precursors, (e.g. DMS, N_2O and BVOCs) may lead to important Earth system feedbacks (Six et al. 2013). Until now these fluxes have had limited explicit representation in ESMs. We will develop and test a set of advanced flux parameterizations for key species in ESMs and evaluate the reliability of simpler empirical parameterizations against the more complex models.

1.4.3 Improving ESM process realism and reliability: Natural aerosol and trace gas processes

The change in aerosols over the industrial era has remained the largest source of forcing uncertainty through all IPCC assessments. Although anthropogenic aerosols will play a small role in climate change in the far future because emissions are projected to decrease, our understanding of climate sensitivity over the next few decades is dependent on knowing the magnitude of net forcing since the pre-industrial era (e.g., Otto et al., 2013). Furthermore, Carslaw et al. (2011) suggest the response of natural systems to climate change could cause large changes in natural aerosol emissions, resulting in a feedback of up to several W m^{-2} by 2100, but with very large uncertainty.

The large diversity of model estimates of forcing, particularly for processes related to aerosol-cloud interaction (ACI), has multiple sources. Many advances have been made in the treatment of aerosols in models and in the specification of anthropogenic emissions. However, models in CMIP5 remain relatively simplistic in their treatment of aerosol processes compared to state of the art in global aerosol models. A major source of model diversity in historical aerosol forcing is likely related to the wide range of aerosol states simulated in the clean pre-industrial era. Carslaw et al. (2013) showed that 45% of the uncertainty in historical aerosol-cloud forcing could be attributed to uncertain natural aerosols. This high sensitivity occurs because cloud albedo is particularly sensitive to changes in aerosols when concentrations are low – the so-called aerosol-limited cloud regime. The simplified way in which most CMIP-type models treat natural aerosol processes means we cannot presently address the large uncertainty in the historical forcing and in how natural aerosols might cause a climate-driven feedback in the future. It is not known how much of the diversity in historical forcings could be reduced by simulating pre-industrial aerosol conditions more realistically, although it is likely to be significant.

In CRESCENDO we focus on natural aerosol emission, deposition, chemical and radiative processes. We aim to simulate a more reliable and evaluated pre-industrial aerosol state (against which historical anthropogenic forcing can be quantified) and to enable comprehensive assessment of how aerosols will respond to future changes in the physical climate and Earth system. Process-guided perturbations of the pre-industrial aerosol state will be used to help quantify uncertainty in anthropogenic aerosol forcing arising from uncertainties in the pre-industrial state. We focus on defining pristine environments in present-day conditions where aerosol properties are dominated by natural processes, allowing models to be evaluated against observations. A set of optimum natural aerosol metrics will be developed and applied to the ensemble of project models. We will investigate how the inclusion of more advanced coupled chemistry-aerosol-cloud processes, linked with equivalent realism in marine and terrestrial biogeochemistry and surface-atmosphere exchanges, affects the representation of natural aerosol-climate interactions. As well as improving the realism of pre-industrial aerosol climates in ESMs, such developments will facilitate investigation of a range of important aerosol-biogeochemistry future feedbacks.

1.4.4 Evaluating ESMs: Bottom-up, process-level evaluation

A key aspect of CRESCENDO is model evaluation. Large uncertainty presently exists in many Earth system model processes, hindering use of ESMs for policy decisions. Targeted evaluation and improvement of these processes is urgently required. Several reviews highlight the important role of both "*top-down*" and "*bottom-up*" evaluation in model improvement (Foley et al 2013). *Top-down* evaluation focuses on full ESMs and *whole-system* outputs, such as average fields of temperature, precipitation, carbon stores etc. Top-down evaluation can be seen as ensuring we *"get the right answer"*. Such whole-system output is often the end result of numerous interacting processes and, therefore, when errors are found it is not readily apparent how to reduce them. Accurate simulations at the *top-down* level can often be achieved by inadvertently introducing compensating errors into models. Hence the need for *bottom-up* evaluation which tests models at the process level, aiming to ensure single components have the right sensitivity to their input drivers. Thus *bottom-up* or *process-level* evaluation can be seen as ensuring models deliver *"the right answers for the right reasons"*. RT2 will deliver a suite of techniques targeting process-level ESM evaluation.

By giving prominence to process evaluation we will increase effort in this important area. Furthermore, by coordinating evaluation, data and software tools we will accelerate the development and use of "*best practices*" and *standard metrics* for ESM evaluation. Finally by developing links between the modelling and observational communities we will ensure optimal use of observations in model evaluation. Process evaluation helps identify which model components, sensitivities and output are most reliable and where projection uncertainty primarily arises from. Documenting the source of this spread is valuable in building trust in models and guiding decision making to aspects of model projections that are most reliable.

1.4.5 Evaluating ESMs: Top-down benchmarking and operational analysis of projections

Top-down evaluation can be routinely applied across models and model generations to chart progress; studies of physical climate models have shown demonstrable improvement between CMIP generations (Reichler and Kim, 2008). *Top-down* evaluation can also used to compare models (Gleckler et al, 2008). This continued improvement leads to increased trust in model projections. Systematic evaluation of ESM biogeochemical and aerosol components remains quite limited with no agreed metrics and datasets that can be routinely applied. For example it is not known whether CMIP5 carbon cycle models perform better than the previous generation C^4MIP models (Friedlingstein et al. 2006). CRESCENDO aims to fill this gap. We will move ESM evaluation beyond the state-of-the-art by investing in routine benchmarking of *physical* and *biogeochemical* aspects of ESMs, as well as developing a quasi-operational approach to analyzing ESM projections. At the conclusion of CRESCENDO *ESMValTool* will run alongside key ESGF nodes, ingesting model output and observational data to benchmark the performance of a given ESM against other ESMs and against observations. The aim is that routine evaluation will become more efficient, more rapidly impact model development and free up time of scientists to concentrate more on model improvement.

1.4.6 Understanding and constraining ESM projections: Emergent Constraints

A realistic representation of processes controlling key climate system feedbacks is expected to improve the credibility of model projections (Knutti et al., 2010a). This is particularly true because correlations between the current *mean* climate and the *mean* state in future projections in essential climate variables (e.g. temperature) are often weak (Knutti et al., 2010b). While a process evaluation of ESMs is important, on its own it does not guarantee the correct response to changed forcing in the future. To evaluate the response of ESMs to a changed external forcing the community has looked to use analogue periods in the paleo record (Otto-Bliesner et al., 2009). Another option, increasingly being investigated, is to combine annual cycle evaluation, with a study of the changing co-variability between forcing and dependent parameters as external forcing changes through the annual cycle (Knutti et al., 2006). The advantage of using the annual cycle or inter-annual variability as a surrogate for a changed external forcing is that errors in the response of the system to such forcing can be directly compared to observations, allowing model improvements that hopefully carry through to the response of the system to other longer-term external forcing changes, such as increasing greenhouse gases (GHGs). This approach was followed by Hall and Qu (2006) who related snow-albedo feedbacks across the annual cycle to inter-model spread of snow-albedo feedbacks in model responses to increasing GHGs. These *emergent constraints* offer a means to focus model evaluation on aspects of the current climate that relate strongly to future projections. Examples include; constraints on future warming from past warming, ocean heat uptake and radiative forcing (Knutti et al., 2002), constraints on climate-carbon feedbacks (Cox et al., 2013) and relating past and future sea ice trends (Mahlstein and Knutti 2012).

Many emergent properties are seen across different models in coordinated experiments, but the interpretation of these ensembles is difficult. Models share biases and often common code, some relationships may emerge as a result of these interdependencies (Knutti et al., 2013). Such dependencies imply the actual number of independent models is much smaller (Sanderson and Knutti, 2012), possibly introducing correlations by chance (Caldwell et al., 2014). Furthermore, a thorough understanding of the processes governing the behaviour of an emergent constraint is crucial for determining the actual realism of such a constraint. A more robust understanding of what various multi-model ensembles represent is required. In CRESCENDO we will quantify how different models are related across hierarchies of complexity, resolution, perturbed parameters and how similarities identified in the present state relate to similarities in the future. Combining this ensemble analysis with a firm theoretical foundation, based on the Fluctuation-Dissipation Theorem, we will ensure the emergent constraints derived will be physically sound and offer real constraints on future Earth System feedbacks.

CRESCENDO brings together world-leaders in *emergent constraints* with leading European ESM teams with the aim of developing process-based emergent constraints targeted on key uncertainties in Earth system projections, Emergent constraints will provide a better estimate of the sensitivity of the real Earth system and a new set of metrics against which ESM projections can be assessed. Combining models and observations with an advanced understanding of the way ensembles can be interpreted will deliver improved guidance on the reliability of Earth system projections and isolate the main feedback terms controlling their magnitude and uncertainty. Through this we aim to deliver *robust* and *trustworthy* Earth system projection information.

1.4.7 Quantifying Feedbacks and Radiative Forcing

The magnitude of climate change is determined by external forcing and numerous feedbacks that can either amplify or dampen the response to that forcing. To determine a scenario of GHG emissions consistent with climate stabilization, physical and biogeochemical feedbacks on a range of time scales have to be understood and with quantified uncertainties. Physical feedbacks, in particular cloud feedbacks, have been confirmed as a primary source of spread in estimates of equilibrium climate sensitivity. However, IPCC AR5 showed uncertainty in biogeochemical feedbacks represent a major impediment to our ability to make reliable projections. It is now accepted that carbon cycle feedbacks will have a significant impact on future climate change through a positive feedback reducing terrestrial carbon storage (Friedlingstein et al., 2006), although large differences exist across models, with even greater divergence likely from the way nitrogen constraints on productivity are modelled (Zaehle et al., 2010). Atmospheric composition feedbacks may also emerge due to methane emissions from wetlands or permafrost (Khvorostyanov et al., 2008), soil emission of nitrous oxide (N_2O), wildfire emissions and emissions of natural aerosols (e.g. dust, sea-salt, DMS, black carbon) (Carslaw et al., 2010).

CRESCENDO will quantify the magnitude of the climate feedback for a number of these phenomena in the project ESMs. A key component of calculating individual feedbacks is quantification of the effective radiative forcing (ERF). These ERFs take into account all fast feedbacks, including biogeochemical processes (Collins et al. 2010). Extending the physical feedback formalism to biogeochemical feedbacks was first proposed by Gregory et al. (2009), with carbon cycle feedbacks analysed in CMIP5 by Arora et al. (2013). We extend this to a wider range of biogeochemical processes (e.g. CO_2 emissions, CH_4 emissions from permafrost and wetlands, sulphate, nitrate, biomass burning), as well as feedbacks involving short-lived species, such as aerosols and ozone. Feedbacks will be diagnosed using a consistent framework to understand the relative importance of each process in future projection size.

1.4.8 Novel socio-economic/emission scenarios and new CMIP6 ESM projections

Given the slow evolution timescale of the Earth system and the different future socio-economic development pathways that might arise, a range of scenarios will always be needed to inform on possible future climate change and climate change impacts. Scenarios also provide a means to connect different groups involved in Earth system science, such as those working on emission trends, Earth system change and climate impacts. An important role in this context is played by *'community'* scenarios, such as the SRES (Nakicenovic et al., 2000) and RCP scenarios (Van Vuuren et al., 2011). There has been clear progress in scenario development; SRES extended the earlier IS92 by considering a wider range of socio-economic developments. The RCPs added a focus on climate policy and mitigation. The RCPs did not include an explicit description of the underlying socio-economic conditions and, therefore, their use in assessing mitigation and adaptation costs is limited. Moreover, the RCPs did not systematically explore the role of aerosols or land-use change on future climate. IAM scenarios predict increasingly steep mitigation costs to achieve low emission scenarios. Hence the role of Earth system feedbacks, such as permafrost thaw and carbon release, could have severe effects on the feasibility of meeting future climate targets. CRESECENDO brings together state-of-the-art in Earth system feedbacks and Integrated Assessment modelling around the ScenarioMIP effort in order to carefully assess such risks.

ScenarioMIP will provide an integrated approach to combining socio-economic scenarios and ESM projections, with a view to address both science and policy questions. New scenarios, building on the RCPs will address aspects related to aerosols, ozone and methane, as well as land use change. Exploring all plausible scenarios will result in a scenario set too big to be usefully sampled by state-of-the-art ESMs. Several approaches have been suggested to reconcile this dilemma, including; selection of priority scenarios, pattern scaling, statistical sampling and the use of lower resolution (computationally faster) ESMs. CRESCENDO will contribute to this discussion, in particular by assessing the performance and projection traceability of lower resolution versions of project ESMs compared to their higher resolution parent models. If an acceptable level of agreement can be established, then it will be possible to generate a large ensemble of projections sampling key CMIP6 scenarios using such lower resolution models. The resulting projection ensemble, combined with the underlying IAM scenarios, will support investigation of interactions between potential policy mitigation options, Earth system change and resulting impact outcomes.

1.4.9 Knowledge and data dissemination

CRESCENDO will provide a step change in the realism of Earth System Models, as well as delivering new and improved Earth system projections. Ensuring this data is accessible to the research community is a high priority for the project. Previous CMIP cycles clearly show the benefit of the international research community analysing such multi-model ensembles. Dissemination to this group will occur through data distribution via the ESGF. CRESCENDO simulations are potentially also of interest to a number of complementary disciplines, such as climate impacts and regional downscaling. It is primarily through these disciplines, where ESM data is translated into higher resolution, regionally-specific impact information, that ESM projections become of direct utility to policy and decision makers. We will ensure key project simulations save fields required for driving Regional Climate Models (RCMs) and statistical downscaling, working closely on this with the FP7 project *Infrastructure for the European Network of Earth System Modelling* (IS-ENES2). Partner SMHI, hosts the new international CORDEX project office, providing a strong link to the regional downscaling community, while partner PIK coordinates ISI-MIP and will be the main link to the climate impacts community. We will maintain a dialogue with both these communities to ensure ESM data is used in the most productive and appropriate way.

These links are an important step in developing a sustainable provision of reliable Earth system change information for Europe.

The final dissemination target for CRESCENDO is policy and decision makers in national and European governments and the interested public. We will move understanding of Earth system modelling and projections towards better communication of the outcomes, processes and methodologies. Our overarching aim will be to maximise the impact of CRESCENDO through concise but understandable knowledge of the next generation of ESMs, encompassing an explanation of the questions they can address, the answers they can provi de and the confidence that can be placed in these answers. A mixture of targeted workshops, policy and public information sheets, training and use of digital/online media will maximise project impact on these target audiences. The CRESCENDO dissemination team is also the dissemination team in the FP7 HELIX project that addresses climate impacts. This will strengthen knowledge and data transfer from ESMs to climate impacts and onto a range of stakeholder groups. Interaction between ESM modellers and impact-adaptation researchers will also provide opportunities for trans-disciplinary knowledge sharing. In collaboration with FP7 HELIX, CRESCENDO will organize training in science communication for young researchers to increase the interest and ability of these scientists to communicate their research to a wide audience.

2. Impact

2.1 Expected impacts

*The **key outcomes** of CRESCENDO include:*

a. An improved set of European ESMs that more realistically represent key *biogeochemical and natural aerosol processes*, as well as interactions between these processes and with the physical climate.

b. A community evaluation tool that supports routine benchmarking of ESMs, quasi-operational analysis of ESM projections and process-oriented evaluation methods.

c. A set of emergent constraints on key Earth system feedbacks, combined with quantification of the radiative forcing of those feedbacks in a common framework and units

d. A new set of combined socio-economic and climate emission scenarios to support ESM projections and co-investigation of the benefits and risks of climate change, impacts, adaptation and mitigation.

e. A coordinated ensemble of ESM projections based on the new CMIP6/ScenarioMIP data, saved on the ESGF and provided in a supported manner to climate impact assessment and regional downscaling projects.

f. Coordinated simulations, saved data and detailed analysis of the project ESMs in support of the CMIP6 Model Intercomparison Projects (MIPs); *C^4MIP, LUMIP, LS3MIP, OCMIP and AerChemMIP*

g. Dissemination of key project knowledge and advances in an engaging and accessible form.

Below we list how the key outcomes of CRESCENDO align with the *“Expected Impacts” section of the call text*.

Improved science based foundation to better assess the impacts of climate variability and change at decadal to centennial time scales, to support the development of effective climate change policies and optimize private decision-making. Robust, credible and trustworthy climate predictions and projections to make in the medium- and long-term European business sectors more resilient and competitive at global scale

<u>*Improving Earth system models to deliver credible and trustworthy projections:*</u> ***Key outcomes a, b, e and f***
We will deliver major advances in the *realism* and *reliability* of European ESMs, providing an improved foundation for the scientific process that delivers *robust*, *credible* and *trustworthy* Earth system projections. CRESCENDO primarily addresses multi-decadal to centennial timescales, on which biogeochemical feedbacks play a key role in global change, as well as a number of environmental responses to this change. Improvement in the representation of such key processes in ESMs is the *only* way to increase the reliability of future Earth system projections. Inclusion of such biogeochemical processes in ESMs also opens up the possibility to study a number of environmental responses to a changing future climate, such as ocean acidification, changed wildfire occurrence, permafrost melt etc.

Bringing all European ESMs currently involved in CMIP into a single project ensures advances will be efficiently shared across Europe. Use of common experiment protocols and evaluation and analysis techniques will aid in the sharing of advances that could not be realized by a set of smaller projects including only a subset of ESMs. By having all these European ESMs in the project we are able to realize an enormous in-kind contribution to the project in terms of; *parallel model development, development of evaluation techniques and technical support and hardware for running ESMs.* CRESCENDO science will be assured pull-through into European ESMs used for the generation of Earth system projections, ensuring a major influence on climate policy at European and national levels.

A number of the phenomena targeted for improvement in CRESCENDO constitute potential tipping points in the Earth system (Lenton et al. 2008), beyond which rapid environmental change may occur. Inclusion of sufficient process realism in ESMs is a necessary step towards providing robust risk assessments of such abrupt changes. While analysis of abrupt change is not a direct objective of CRESCENDO, the improvements we target will make the resulting models more suitable for investigating such risks. Geoengineering, or "Climate Engineering", is increasingly discussed as a potential component of climate mitigation policies, either through Solar Radiation Management (SRM) or Carbon Dioxide Removal (CDR). Possible effectiveness and consequences of such actions were assessed for the first time in IPCC AR5. Earth System modelling has the potential to address many key research gaps in this area (Jones et al. 2013). Whilst not part of CRESCENDO, model developments, and scenario assessments made in the project will contribute to geoengineering activities through GEOMIP (Kravitz et al. 2013) or MAGNET ("Managing Global Negative Emissions Technology"), an activity of the Global Carbon Project, Fuss et al. (2014).

Driving forward the quality of ESMs through continuous evaluation: ***Key outcomes a and b***
Development of a community ESM evaluation, benchmarking and analysis tool is an important contribution to future ESM development, both with respect to model improvement and for rapidly assessing ESM simulations, reducing the time required to bring such information into the policy domain. A shared evaluation tool reduces duplication of effort, allowing sharing of methods. ESMValTool will be made freely available and installed on a number of ESGF data nodes, allowing direct analysis of CMIP multi-model data without the need for extensive data transfer. Work in this area will closely align with the WGNE/WGCM Climate Model Metrics panel.

Emergent constraints on Earth system projections and quantifying climate feedback parameters: ***Key outcomes a and c***
We will develop and apply the discipline of *emergent constraints* to CRESCENDO simulations, as well as other CMIP5 and CMIP6 data. Through this we aim to quantify and reduce uncertainty in key feedbacks underpinning the magnitude of future Earth system change. This will be achieved by linking common multi-model future Earth system responses to observable aspects of present-past climate variability. Multi-model representations of the latter, observed variability can then be compared to observations and used to constrain the magnitude of the simulated (non-observable) future feedback. This will help to reduce overall uncertainty of future climate estimates while targeting model development onto phenomena underpinning the magnitude and uncertainty of future Earth system change.

Supporting the use of ESM knowledge and data in key complementary disciplines. ***Key outcomes a, d and e.***
Collaboration with climate impact assessment and regional climate downscaling groups will ensure CRESCENDO delivers actionable information to support European decision-making. Increased collaboration between disciplines is crucial for efficient and cost-effective delivery of robust and useable Earth system change information. ESM projections are at the top-end of this chain, providing forcing data directly to climate impact models and boundary conditions to either dynamical or statistical downscaling methods, through which ESM projections are regionalized to higher spatial resolution. The quality of regional climate change information and derived climate impacts is therefore directly dependent on the quality of ESM projections. While we do not directly address climate impacts or regional downscaling in CRESCENDO, we do have experts from these disciplines in the consortium who will provide a sustained collaboration with, respectively, the ISI-MIP and HELIX projects and WCRP CORDEX. In collaboration with these projects we will improve the usability of ESM simulation data through application of reliable bias-correction methods. ESM data will be provided through a sustained two-way dialogue, maximizing utility of our simulations in the knowledge chain delivering Earth system change information to policymakers and the public.

<u>*Training future scientists to be good communicators of their research.*</u> ***Key outcome g***
CRESCENDO will work with other European efforts to train the next generation of scientists to be effective communicators of their research. The inter-disciplinary nature of this collaboration, between Earth System modelers (CRESCENDO) and impact scientists (HELIX/ISI-MIP), will ensure training covers the necessary breadth while providing the opportunity to build future collaborations across diverse communities.

<u>*Knowledge Dissemination: A key support for policy and public decision-making.*</u> ***Key outcomes a, d, e and g***
Active dissemination will ensure CRESCENDO science is accessible to the public through a range of channels including; web and social media, science fairs and conferences and targeted information sheets. Our dissemination team has extensive experience working with the science media and will keep developments in the project visible and engaging to the public. The team also has experience working with governments and the European Commission, ensuring key knowledge is presented in an accessible manner while remaining scientifically credible. We will hold a number of major dissemination events on new CMIP6 Earth System projections and policy relevant outcomes of these projections, collaborating with other Horizon2020 and FP7 projects to maximize the usefulness of knowledge delivered while avoiding duplication of events. Collaboration on dissemination is already established with the HELIX project. Furthermore, SMHI hosts the International CORDEX Project Office and will be responsible for knowledge dissemination across CORDEX. Our dissemination team therefore covers all parts of the information chain from ESMs, through regionalization to climate impact assessment and the delivery of actionable information. This breadth of knowledge will increase the quality of information delivered by the project and offers the potential to lead a Europe-wide activity to develop useable climate change risk assessments.

Project outcome should support the post-AR5 IPCC process and other relevant international scientific assessments, and provide a solid scientific basis for future science cooperation and policy actions at European and international level.

<u>*Supporting International activities in Earth system science and modeling.*</u> ***Key outcomes b, d, e and f***
CRESCENDO is the main European contribution to CMIP6/ScenarioMIP, generating new Earth System projections post CMIP5/AR5. Over the next 5 years it will be the primary European collaboration targeting development and improvement of ESMs, in particular the representation of key biogeochemical and natural aerosol processes in these models. Such parameterizations remain relatively early in their development and evaluation compared to more mature physical climate components of ESMs. CRESCENDO therefore constitutes a key platform for driving future improvement in some of the key uncertain processes in ESMs.

Working within ScenarioMIP we will generate a combination of IAM scenarios and ESM projections suitable for integrated analysis of climate change, climate impacts, adaptation and mitigation. ScenarioMIP projections will be disseminated to complementary research communities through a sustained dialogue to ensure maximum uptake and utility. The full ScenarioMIP ensemble, combined with associated work in areas such as downscaling, impact assessment and adaptation-mitigation, will be a major component of the Earth system science knowledge available to future IPCC assessments. CRESCENDO represents an important European contribution to this foundational science. ESMValTool will provide an *easy-to-apply* and *easy-to-extend* facility to benchmark future ESM performance and to make a range of multi-model assessments, including analysis of future projections. CRESCENDO will also be the main European contribution to further 5 Model Intercomparison Projects contributing to CMIP6 (*C^4MIP, LUMIP, LS3MIP, OCCMIP and AerChemMIP*).

<u>*Collaboration through international bodies and with key partners.*</u> ***Key outcomes b, d and f***
We will use the high standing of consortium partners to ensure work in the project is communicated across a range of international advisory bodies, in particular the WCRP Working Group on Coupled Modeling (WGCM) and the CMIP panel. CRESCENDO partners include;

- *The chair of the CMIP panel and co-chairs of the International Geosphere-Biosphere Programme (IGBP) Analysis, Integration and Modeling of the Earth System (AIMES), ISI-MIP, GEWEX, and the Global Carbon project science steering committee.*
- *Chairs of ScenarioMIP, AerChemMIP, C^4MIP, LS3MIP and OCMIP as well as active contributors to LUMIP.*
- *Members of the following panels; WGCM, IGBP-AIMES, WGNE/WGCM Climate Model Metrics panel, and WCRP Data Advisory Council (WDAC) Observations for Model Evaluation Task Team and the ESA CCI Climate Model User Group (CMUG)*

- *Former co-chair of CORDEX, the host institute of the International Project Office for CORDEX and member of the CORDEX Science Advisory Team.*
- *The lead institute for the ISI-MIP climate impacts project.*
- *Members of the Future Earth science advisory board*
- *Four Coordinating Lead Authors, twelve lead authors and one review editor of IPCC AR5*

Furthermore, seven European ESM teams are represented in the consortium through senior scientists from these centres, ensuring pull-through of science developments into European ESMs and, conversely, a broad in-kind contribution from the centres to CRESCENDO. In particular, CRESCENDO will ensure regular interaction with JPI-climate (the Joint programming initiative for climate) and the new Copernicus Climate Services initiative. Through these channels we will ensure knowledge developed in the project is effectively disseminated to, and influences, the international science community and conversely, that developments made elsewhere influence CRESCENDO research. Structuring CRESCENDO around international activities means European contributions to CMIP6 can be made in a coordinated manner, while providing a mechanism for groups to be well integrated into these international activities.

2.2 Measures to maximise impact

2.2.1 Dissemination and exploitation of results

As outlined above the five key target groups for dissemination of CRESCENDO results are:

1. The international climate and Earth system science community
2. The international regional downscaling community
3. The climate impact modelling community
4. Policy and decision makers in national and European government departments
5. Lay specialists such as NGO's, journalists, and in particular the interested public

The table below summarizes the tools and channels that will be utilised to reach these target audiences and how this will help achieve the expected project impact.

Audience	New knowledge	Dissemination tools/channels	Resulting impact
International climate and Earth Science Community (including Early Career Scientists: ECS')	CRESCENDO data, particularly CMIP6 simulations	Upload data to the ESGF together with development of existing collaborations within the ESM community.	Coordination of European contributions to CMIP6 and ensuring open access of project simulations.
	Further development of an openly available community ESM evaluation tool	Distribution of the tool and support for users and developers.	ESMValTool will allow routine benchmarking and advanced analysis of ESM processes, projections and feedbacks.
	New knowledge and advances in ESM science.	Open access publications, presentations at conferences and workshops and development of scientific collaborations.	Developments made in the project will be shared across the research community to ensure maximum impact and reduce any duplication of effort.
		Training of young scientists through project-funded PhD and post doc positions.	Opportunities for ECS' to be involved at the forefront of ESM development and interaction with leading scientists in the field.
	Communicating science skills	Collaborating on science communication training with HELIX and ISIMIP community.	Improving communication skills of ECS' will allow more effective future links with stakeholders.
Regional downscaling community	Provision of CRESCENDO data to regional downscaling	Utilisation of SMHI's position as host of CORDEX office to disseminate to this group	Efficient and cost-effective delivery of ESM data for regional climate downscaling.

Climate impacts communities	Provision of CRESCENDO data for impact models. Development of bias correction methods.	Guidance notes, plus workshop, on accessing and using CRESCENDO and other ESM data	Ensure climate impacts users are aware of the availability, and are able to effectively utilise, CRESCENDO data for climate impacts assessment.
	New knowledge and advances in ESM science.	Development of existing (HELX, ISIMIP, IMPACT2C), and initiation of new collaboration (e.g. PROVIA) for effective knowledge dissemination.	Raising awareness of new simulations will allow higher quality information for climate impacts, adaptation and mitigation studies.
Technical policy users (national and international)	New knowledge in ESM science. Policy relevant scenarios and projections.	Concise and responsive guidance notes and targeted workshops on policy relevant project findings.	Effective and targeted information provided directly to the technical advisors of policy and decision makers.
Lay specialists (NGOs, Young People, Journalists)	How well do models represent the climate? How are they built? What do they tell us about the future? How reliable are they?	Online / YouTube Channel / Animation. On line information sheets. Science fairs.	Improving public understanding of Earth system science. Potentially encouraging young people to consider a career in climate science.

Table 2: Tools and channels for project dissemination

Data management

CRESCENDO will generate large volumes of data and therefore a Data Protocol Panel (DPP) will be formed (see section 3.2.1). Data will be saved on the ESGF following CMIP6 guidelines. The DPP will develop a Data Management Plan (DMP) in the first six months of the project and be responsible for its adherence by all partners. The DPP will maintain close collaboration with the WGCM Infrastructure Panel and with the FP7 projects, is-ENES2 and the Climate Information Platform for Copernicus (CLIP-C), as well as the G8 project Exascale Archives (ExArch).

Knowledge management and protection

CRESCENDO will fully adhere to the open access policy and requirements laid out in article 29.2 of the Model Grant Agreement. Each partner, supported by the project office, will be responsible for ensuring that CRESCENDO funded publications are appropriately acknowledged, deposited in an appropriate repository for scientific publications (such as OpenAIRE), and provided with gold (if possible) or green open access, including bibliographic metadata. The project office will aid partners to provide open access (where appropriate) to other forms of publications such as books, reports, conference proceedings and grey literature, primarily through the public project website and associated use of social media platforms.

2.2.2 Communication activities

In the above table 2 the main tools and channels utilised in CRESCENDO dissemination are outlined and can be grouped as follows: (a) dissemination of model data through the ESGF and interaction with the climate impacts and regional downscaling communities on best use of this data; (b) distribution and support of ESMValTool; (c) open access scientific publications; (d) guidance notes targeted to the needs of relevant groups (e.g. the policy community, the impact assessment community); (e) development of collaborations to widen dissemination scope, increase impact, and reduce duplication of effort; (f) communication training for young scientists; (g) an online presence and (h) workshops targeted to policymakers. These measures will ensure CRESCENDO outcomes reach their intended audience in the most effective manner.

3. Implementation

3.1 Work plan — Work packages, deliverables and milestones

Work package number	1.1	**Start Date or Starting Event**				Month 1-60					
Work package title	Improving ESMs: Terrestrial biogeochemical processes										
Participant number	6	5	3	2	13	17	12	22	19	4	9	24
Short name of participant	UNEXE	MOHC	MPG	CNRS-IPSL	MF-CNRM	UiB	ENEA	CNR	ULUND	CMCC	METNO	FMI
Person/months per participant	27	24	42	32	12	11	15	12	15	25	5	10

Objectives

This WP will improve the terrestrial components of the project ESMs. Developments will focus on coupling of two major terrestrial biogeochemical cycles, carbon and nitrogen, improvement of newly implemented modules of wetlands and methane (CH_4) emissions and on improved representation of land cover and land use change in ESMs. The WP is linked to the WP2.1, which will perform process-level evaluation of offline simulations of the terrestrial ESM components. The WP contributes to three series of CMIP6 terrestrial intercomparison exercises: C^4MIP for biogeochemical cycles, LUMIP for land use and land change interactions and LS3MIP, which studies surface biophysical and hydrological processes. Working with C^4MIP, LS3MIP will also consider surface biophysical-biogeochemical interactions, while in collaboration with LUMIP interactions between surface biophysics, biogeochemistry and land use change will be addressed.

Description of work

Task 1.1.1: Carbon and nitrogen dynamics in vegetation and soils (<u>UNEXE</u>, MOHC, MPG, CNRS-IPSL, UiB, ULUND, CMCC, METNO)

The carbon cycle on land is tightly coupled to nitrogen, the main limiting nutrient to plant growth. All project ESMs have an interactive land carbon cycle, with however, a large spectrum of complexity regarding the nitrogen cycle. This task aims to consolidate the nitrogen component of the land ESMs in order to simulate nitrogen limitation of terrestrial land carbon uptake and the effect of this limitation on climate - carbon cycle feedbacks. The task will also focus on improving interactions between land and atmosphere via N_2O emissions. Main developments will be on nitrogen mineralisation, plant uptake of nitrogen, inclusion of atmospheric deposition of nitrogen, and representation of NO_x and N_2O emissions from soils. The task will interact with the task 2.1.1 by (i) performing site-level simulations of land surface models to evaluate the land carbon cycle response to atmospheric CO_2 increase based on FACE experiments (Zaehle et al., 2014) and (ii) evaluating the effect of C-N interactions on soil carbon storages. The evaluation protocol, offline C-N and key C^4MIP simulations will be done in this task.

Task 1.1.2: Wetlands and permafrost systems and methane emissions (<u>MOHC,</u> MPG, CNRS-IPSL, MF-CNRM, ULUND, CMCC,FMI)

Wetlands and permafrost ecosystems are net sources of CH_4 to the atmosphere. Climate change and associated changes in surface hydrology will affect the distribution and rate of emissions of CH_4, as well as the decomposition of peat. Warming at high latitudes will lead to permafrost soils thaw, resulting in formation of wetlands, organic matter decomposition and release of CO_2 and CH_4 to atmosphere. CRESCENDO ESMs will further develop the representation of these methane-emitting ecosystems, including different types of wetland ecosystems, treatment of topography, overbank and flooded plains, soil water table mechanisms, and CH_4 emissions for both wetlands and permafrost. Improvements in the representation of soil thermal and hydrological processes, including effects of a soil organic layer on heat and water conductivity will be implemented into land surface models. The models will be evaluated against available data in WP2.1.2.

Task 1.1.3: Land use and Land cover in ESMs (MPG, UNEXE, MOHC, CNRS-IPSL, UiB, ENEA, CNR, ULUND, CMCC, METNO, ETH)

The goal of this task is to consolidate land/vegetation developments that relate to the representation of land cover, land use and land management in different ESMs. The 1st subtask is to remove artificial uncertainty associated with incoherent land use representation in models and to prepare ESMs for analysis of land use effects on climate in LUMIP and LS3MIP experiments (to be performed in this task). We plan to implement gross transitions and wood harvest coherently across models. We will analyse the effect of biases in vegetation cover on carbon fluxes. Site-level evaluation of soil carbon storage changes due to landuse will be done in interaction with WP2.1 using observed chronosequences of soil carbon after transformation of natural forests or grasslands into agroecosystems

The 2nd subtask is to improve the representation of complex forest structure (e.g. multi-species, uneven age and multi-layered forests), taking into account the main structural drivers that control forest dynamics (Collalti et al., 2014). An important aspect is to simulate forest age classes and to assess the effects of forest structure on carbon and water fluxes. A special focus will be also on representing the effects of ecosystem multi-stability due to different ecological processes (Hirota et al., 2011), including disturbances such as fire (together with WP1.3), and analysis of possible effects of ecosystem instability on land carbon storage. This task will interact with the task 2.1.3 on benchmarking of vegetation cover.

Table 1.1.1. Terrestrial components in ESM to be improved (Y) or used (U) in WP1.1. N is for not used.

Participant / Model	C-N interaction	N_2O emissions	Wetlands permafrost	CH_4 emissions	Land use	Forest structure
UNEXE/ UKESM	Y	Y	-	-	Y	Y
MOHC / UKESM	Y	Y	Y	Y	-	-
FMI / UKESM	-	-	Y	Y	-	-
MPG / MPI-ESM	Y	U	Y	U	Y	U
CNRS-IPSL / IPSL-CM	Y	Y	Y	U	Y	U
UiB / NorESM	U	N	U	U	U	U
ENEA / EC-Earth	-	-	-	-	Y	-
CNR/EC-Earth	-	-	-	-	-	Y
ULUND/ EC-Earth	Y	Y	Y	Y	Y	Y
CMCC / CMCC ESM	Y	N	N	N	U	Y
CNRM/CNRM-ESM	-	-	Y	-	U	U

Deliverables

D2.1 Report describing improved representation of terrestrial processes in European ESMs (M60)

Milestones

M1.1.1 Protocol of model simulations for evaluation tests ready (M6)
M1.1.2 1st set of offline simulations with improvements in terrestrial processes delivered to WP2.1 (M24)
M1.1.3 Consolidated representation of land use in ESMs (M24)
M1.1.4 Key C^4MIP simulations performed (M34)
M1.1.5 Key LUMIP simulations performed (M36)
M1.1.6 Key LS3MIP simulations performed (M38)
M1.1.7 2nd set of offline simulations with further improved terrestrial processes delivered to WP2.1 (M52)
M1.1.8 Final improved versions of terrestrial modules implemented into project ESM (M60)

Work package number	1.2		**Start Date or Starting Event**				Month 1-60
Work package title	Improving ESMs: Marine biogeochemical processes						
Participant number	21	14	3	2	13	17	10	4
Short name of participant	NOC	UEA	MPG	CNRS-IPSL	MF-CNRM	UiB	SMHI	CMCC
Person/months per participant	22	19	32	37	21	24	12	34

Objectives

This WP focuses on marine biogeochemical processes involved in Earth system feedbacks and aims to improve their representation in ESMs. We will improve the representation of air-sea CO_2 fluxes and the overall ocean carbon cycle, as well as explicitly include marine emissions of some climate-active species (N_2O, DMS, VOCs). To guide the choice of target processes, we rely on the recent IPCC 5th assessment report (IPCC, 2013) that identifies; *small-scale ocean physics, coastal ocean processes, variable nutrient ratios and loss processes of marine organic matter, interactive atmospheric deposition and riverine input of key fertilizing species* as among the most important processes missing or poorly represented in marine biogeochemical models. The WP is linked with WP2.2 through the use of constrained ocean simulations and process-level evaluation of the target marine ESM components. Regular interaction will occur with WP1.3 where atmospheric emission/deposition of marine gases and aerosols is addressed. The WP will contribute to OCMIP and C^4MIP.

Description of work

Task 1.2.1: Improved ocean dynamics & impact on marine biogeochemical cycles (<u>NOC</u>, MPG, CNRS-IPSL, UiB, SMHI, CMCC)

Marine biogeochemical tracers simulated by CMIP5 models suffer from larges biases in ocean dynamics (e.g., Sallée et al. 2013). Improvements in the representation of the ocean mixed layer and in deep-ocean ventilation will result in a better representation of ocean carbon and other biogeochemical cycles (Séférian et al. 2013, Ilyina et al. 2013). Coastal processes and ocean-shelf exchanges, which contribute to the global GHG budgets (Regnier et al. 2013) are poorly represented in current generation models, thereby not accounting for a substantial amount of matter turnover (nutrients, carbon) in shallow seas. Upwelling systems and oxygen minimum zones are also not well captured (Cocco et al. 2013; Andrews et al., 2013). Improvements in both systems (coastal and upwelling regions) are anticipated as a result of a better representation of the underlying physical processes through higher model resolution. In this task, we use increased vertical and horizontal resolution ocean models (from ~1-2° in CMIP5 to ~¼° in CMIP6), as well as improved physical processes (vertical mixing, tidal mixing, improved bathymetry) and advanced methods of equilibration of the marine biogeochemistry. We focus on the role of improved ocean dynamics on (1) air-sea CO_2 fluxes in the open-ocean, (2) on the carbon cycle in the shelf and coastal systems and their impact on the full ocean carbon cycle, and (3) on the representation of oxygen minimum zones (OMZs) in upwelling regions. These improvements will be evaluated against observational data in WP2.2.

Task 1.2.2: Improved representation of organic matter cycling (<u>MPG</u>, UEA, CNRS-IPSL, MF-CNRM, UiB, CMCC)

While improvement of simulated marine biogeochemical processes are anticipated as a result of better representation of the underlying physical processes (task 1.2.1), increased model resolution alone is not sufficient and improvements in biogeochemical processes are also necessary (Ilyina et al., 2013). Most ESM marine biogeochemical modules rely on simple parameterizations of biological/biogeochemical processes. This is particularly the case with respect to sinking processes, bacterial and other loss processes (Kwon et al. 2009) and the representation of coupled carbon-nitrogen dynamics (Gruber 2011). Some of these processes could lead to changes in the ocean CO_2 sink or in other biogeochemical cycles (e.g. extension of OMZs), in particular temperature effects on marine ecosystem processes and variable nutrient ratios induced by ocean acidification or ecosystem changes (Tagliabue et al., 2011).

In this task, we will Improve the “flexibility” of some of these parameterisations through (1) the use of variable nutrient ratios for organic matter production as a function of ecosystem changes and ocean acidification. We will also improve organic matter loss processes through focusing on (2) an explicit representation of variable lability for dissolved organic matter and (3) on the marine N-cycle and its role in C loss processes (e.g. sediment and water-column denitrification, annamox processes).

Task 1.2.3: External input of nutrient and emission of trace gases (<u>UEA</u>, CNRS-IPSL, MF-CNRM, UiB, CMCC)

Atmospheric transport of gas and aerosol species and subsequent deposition on the open ocean, as well as riverine input of dissolved species, can provide important external nutrient sources to marine ecosystems (e.g. Seitzinger et al; 2010). Studies highlight the significance of deposition fluxes from anthropogenically derived reactive nitrogen (NOy + NHx) (Dentener et al. 2006), the role of mineral dust deposition as a source of iron to marine phytoplankton (Jickells et al. 2005) and the role of riverine input of nutrients (N, P, Si, Fe) on marine chlorophyll and productivity (da Cuhna et al. 2013). Variations in these nutrient fluxes can also result in potentially important changes in ocean-atmosphere exchange of radiatively significant species such as CO_2 (Regnier et al. 2013). These nutrient flux pathways and their variability have not commonly been included in ESMs. This sub-task will further develop the ocean biogeochemistry modules of the project ESMs to account for such external nutrient source inputs, and assess their impact on marine biogeochemistry. The sub-task will be linked to WP 1.3.3, which will provide the atmospheric deposition fluxes of reactive nitrogen and soluble iron from the ESM atmospheric composition modules.

Changes in biogenically derived ocean fluxes of climatically important trace-gases could lead to Earth system feedbacks (Six et al. 2013), up to now these fluxes have had limited representation in ESMs. There is a need to develop reliable and computationally efficient parameterizations of these emissions for the next generation of ESMs. In this sub-task, we implement a set of parameterizations (of varying levels of complexity) for key species (DMS, N_2O, and selected BVOCs) in the ocean biogeochemistry component of the project ESMs. Ocean-atmosphere fluxes of these species will be calculated by the marine biogeochemical modules, and provided to the atmospheric composition modules of the project ESMs. This ocean-atmosphere coupling will be addressed through collaboration with WP 1.3 and evaluated in WP2.3.

Table 1.2.1. Marine components in ESM to be improved (Y) in WP1.2.

Participant / Model	Increased Model Resolution	Improved physical param.	Organic Matter Stoechiometry & Lability	N-Cycle processes	Atm. deposition / River input	Trace gas emissions
NOC / UKESM	Y	Y	-	-	-	-
UEA / UKESM	-	-	-	Y	Y	Y
MPG / MPI-ESM	Y	Y	-	Y	Y	-
CNRS-IPSL / IPSL-CM	Y	-	Y	-	Y	Y
CNRM / CNRM-ESM	-	-	Y	-	Y	Y
UiB / NorESM	Y	Y	-	Y	Y	Y
SHMI / EC-Earth	Y	Y	-	-	-	-
CMCC / CMCC ESM	Y	-	Y	Y	Y	-

Deliverables
D1.2.1 Report describing improved marine process in European ESMs (M60)
Milestones
M1.2.1 (Joint with OCMIP) milestone on agreed protocol for ocean forced simulations (M6)
M1.2.2 1st set of offline simulations with improvements in marine processes provided to WP2.2. (M24)
M1.2.3 Key OCCMIP simulations performed (M36)
M1.2.4 2nd set of simulations with further improvements in marine processes provided to WP2.2. (M52)
M1.2.5 Final improved versions of marine modules implemented in European ESMs (M60)

Work package number	1.3	**Start Date or Starting Event**					Month 1-60		
Work package title	Improving ESMs: Natural Aerosols and trace gases								
Participant number	5	13	2	8	22	1	9	19	6
Short name of participant	MOHC	MF-CNRM	CNRS-IPSL	KNMI	CNR	UNIVLEEDS	METNO	ULUND	UNEXE	FMI
Person/months per participant	32	24	32	32	9	20	32	8	8	0 *(12 in-kind)*

Objectives
This WP focuses on the representation of natural aerosol and gas-phase processes in ESMs combined with an improved treatment of terrestrial and marine feedbacks, mediated through aerosols and reactive gases.

The WP is linked to terrestrial and marine process developments in WP1.1 and 1.2 and for evaluation to WP2.3. The WP contributes to the CMIP6 MIPs: AerChemMIP for atmospheric chemistry and aerosols, C^4MIP through wildfire and biogenic emissions and ScenarioMIP for projections of climate and composition.

Description of work

Task 1.3.1 Emissions of Terrestrial Aerosols and Trace Gases

a) Wild Fires and Biogenic Emissions (ULUND, KNMI, CNR, UNEXE, UNIVLEEDS)

Fires are a natural component of the life cycle of an ecosystem and climate change may affect their frequency and intensity. Increased aridity in tropical and subtropical regions may lead to an increase in fire activity, with emissions of greenhouse gases (CO_2 and CH_4), organic aerosols and ozone precursors. Such an increase in fire regime could trigger transitions from forest to savannah, with implications for carbon storage. Implementation of fires in ESMs is in its infancy. We will include currently developed fire modules in the project ESMs, with a focus on processes driving ignition, fire intensity and damage and post-fire recovery. Emissions will be coupled to the ESM chemistry-aerosol modules and evaluated in WP2.3.

b) Terrestrial Emissions of BVOCs (MOHC, CNRS-IPSL, UNIVLEEDS, KNMI, FMI)

BVOCs affect the concentrations of some radiatively important atmospheric gases: CH_4 through changes in lifetime due to OH, tropospheric O_3 and secondary organic aerosols (SOA). BVOC emissions are modulated by temperature, radiation and the state of the vegetation. This task will ensure interactive BVOC emission modules are implemented and coupled to the chemistry and aerosol components of participating ESMs, including in-kind contributions from FMI.

c) Terrestrial mineral dust emissions (UNIVLEEDS, CNRM, CNRS-IPSL, METNO)

Mineral aerosol is emitted both naturally and as a result of anthropogenic disturbances. Optical properties of mineral dust lead to a positive radiative effect over bright surfaces. There are large uncertainties in dust concentrations and optical properties in models (Ryder et al., 2013), and in the anthropogenic fraction of dust (Ginoux et al., 2012). Emission parameterizations will be improved with regard to size distributions and soil characteristics. Improved emission schemes, accounting for the iron content of emitted particles will be coupled to the terrestrial model components and evaluated in task 2.3.1.

Task 1.3.2 Emissions of Marine Aerosols and Trace Gases

a) Emission of biogenic aerosol, sea salt and trace gases (METNO, UNIVLEEDS, MF-CNRM, CNRS-IPSL)

Atmospheric sulphur in project ESMs will be coupled to DMS emissions from marine biogeochemical models (WP1.2). Primary marine bio-aerosols consist of living or dead material from ~10 nm to 0.1 mm in diameter. Such aerosols constitute a source of natural background aerosols over remote marine areas together with sea salt and particles oxidized from DMS (Spracklen et al., 2008, Lapina et al., 2011). We will improve the representation of marine particles from both DMS and primary bio-aerosols and use estimates of the oceanic content of biological material and wind speed to calculate emissions of primary bio-aerosols. Sea salt is an important component of natural aerosol, important for its direct and indirect effects on radiation and as a critical term in heterogeneous chemistry. New emission parameterizations for sea salt, based on recent laboratory data, will be tested in the project ESMs. The NorESM2 sea-ice component will also be upgraded by including prognostic salt in sea ice, which will directly influence the emission fluxes of sea-salt aerosols, and indirectly the fluxes of other marine aerosols due to changed buoyancy of polar water masses. Implications of this for sea-ice melt and ocean mixing will be shared with other partners.

Task 1.3.3. Atmospheric Processing and Deposition of Aerosols and Trace Gases

a) Coupling nitrogen deposition to terrestrial and marine carbon cycles (KNMI, MOHC, CNRS-IPSL, METNO)

Reactive nitrogen is an important nutrient for both the terrestrial and marine biosphere, the availability of which is strongly impacted by human activities. Low nitrogen availability will likely be a limiting factor for carbon storage on land in the 21st century (Ciais et al., 2014), while atmospheric nitrogen deposition to the ocean can also have a strong effect on marine biology (Krishnamurthy et al., 2009). Atmospheric ESM composition modules will calculate time varying deposition patterns of NOy and NHx and be coupled to both the terrestrial and the marine biogeochemistry components of the same models to allow an integrated treatment of the nitrogen cycle and impacts on the marine carbon cycle.

b) BVOCs, secondary organic aerosol formation, processing and deposition (CNRS-IPSL, MOHC, METNO, UNIVLEEDS, FMI)

BVOCs affect the concentrations of radiatively important atmospheric constituents: CH_4, tropospheric O_3 and secondary organic aerosols (SOA). Globally, the amount of SOA is expected to increase due to increases in BVOC emissions, resulting in additional radiative cooling (Carslaw et al., 2010). In many ESMs SOA is prescribed rather than modelled explicitly (Tsigaridis et al., 2014). SOA formation schemes in the project ESMs will be improved, including in-kind contributions from FMI. Improvements will include; isoprene oxidation and species volatility to determine gas/particle partitioning. Both advanced and simplified SOA schemes will be evaluated (WP2.3 in RT2), together with coupling to BVOC emissions from dynamic vegetation components (Task 1.3.1b). Atmospheric transport and chemical processing of DMS and biogenic aerosols will be evaluated in the project ESMs linked to the emissions work carried out in Task 1.3.2a

c) Dust optical, microphysical and biogeochemical processes (MF-CNRM, UNIVLEEDS, MOHC, CNRS-IPSL)

Mineral aerosol is emitted naturally or as a result of anthropogenic disturbances and can lead to a positive radiative effect over bright surfaces. We will introduce improvements in the optical properties of dust (making better use of the size distribution and mineral content) in a subset of project ESMs and build on the emissions developments in Task1.3.1c. Mineral aerosol is also an important source of soluble iron and phosphorus to both marine and terrestrial domains. While transported in the atmosphere, variable mineralogical composition and cloud processing are responsible for large variations in the soluble iron deposited. It has recently been suggested that phytoplankton dynamics in the subtropical Atlantic is controlled by the ITCZ through iron deposition and that atmospheric circulation changes could modify ocean carbon uptake through this mechanism (Schlosser et al., 2013). Deposition fields of soluble iron have not been compared in atmospheric models to date and will form part of the evaluation in WP2.3.

Table 1.3.1. Chemistry/Aerosol components in ESM to be improved (Y) or used (U) in WP1.3.

Participant / Model	Fire emissions	BVOC emissions	Dust emissions	Sea salt emissions	Nitrogen deposition	SOA	Dust/Iron
UNEXE/ UKESM	Y						
MOHC / UKESM	U	Y	U	U	Y	Y	Y
UNIVLEEDS/UKESM	U	Y	Y	Y		Y	Y
CNRM/CNRM-CM		Y	Y				Y
IPSL / IPSL-CM		Y	Y	Y	Y	Y	Y
METNO/NorESM		Y	Y	Y	Y	Y	
FMI / EC-Earth		Y				Y	
KNMI/EC-Earth	Y	Y			Y		
CNR/EC-Earth	U						
ULUND/ EC-Earth	Y						

Deliverables

D1.3.1:Report describing improved representation of natural aerosol and trace gas processes and couplings in European ESMs (M60)

Milestones

M1.3.1 Protocol of model simulations for evaluation tests ready (M6)
M1.3.2 Initial set of atmospheric simulations with improved processes provided to WP2.3 (M24)
M1.3.3 Key AerChemMIP simulations performed (M36)
M1.3.4 Improved coupling between terrestrial emissions and chemistry/aerosol components (M48)
M1.3.5 Improved coupling between marine emissions and chemistry/aerosol components (M48)
M1.3.6 Improved SOA schemes and deposition to terrestrial and marine carbon cycles (M48)
M1.3.7 Second set of atmospheric simulations with improved processes provided to WP2.3 (M52)

Work package number	2.1	**Start Date or Starting Event**			Month 1-60				
Work package title	Evaluating Terrestrial Processes in ESMs								
Participant number	4	12	16	6	2	22	5	3	19	24

Short name of participant	CMCC	ENEA	ETH	UNEXE	CNRS-IPSL	CNR	MOHC	MPG	ULUND	FMI
Person/months per participant	9	6	9	7	12	6	19	22	8	8

Objectives

WP 2.1 will develop and apply new observational constraints for process-parameterizations developed in WP 1.1. We will develop a set of top-down metrics to assess the magnitude and spatio-temporal patterns of simulated fluxes based on a combination of remote-sensing data and bottom-up products integrating in situ measurements. WP 2.1 will further develop dedicated bottom-up metrics to assess process-level responses to global change of particular processes (e.g. the CO_2 response of terrestrial C storage). These metrics will be made available to the consortium to test improvements made during CRESCENDO. Suitable, new top-down and process-oriented diagnostics and performance metrics will be integrated into ESMValTool.

Description of work

Task 2.1.1: Carbon and nitrogen dynamics in vegetation and soils (MPG, MOHC, ULUND)

This task will generate new metrics to constrain global carbon storage and turnover in ESMs, based on development of existing datasets (Jung et al., 2011). These data will be used to derive performance metrics that assess the sensitivity of stocks and turnover rates to climate drivers (temperature, precipitation, radiation), allowing for an assessment of carbon cycle simulations from both offline and fully coupled simulations. To further evaluate new carbon-nitrogen cycle coupling developed in Task 1.1.1, Task 2.1.1 will apply the bottom-up model evaluation techniques derived from a recent model-data synthesis of carbon and nitrogen cycle response to CO_2 enrichment experiments (Zaehle et al. 2014) to evaluate the adequacy of the new process formulations. The sensitivity of models to elevated CO_2 and N inputs will be assessed using global-scale sensitivity studies branched off from existing offline simulations (e.g. the response to step increase in CO_2 or N inputs), which will be compared to meta-analysis of experimental evidence.

Task 2.1.2: Wetlands, permafrost and methane emissions (MOHC, FMI, CNRS-IPSL, ULUND)

This task will develop and implement bottom-up metrics of permafrost physics in ESMs including the sensitivity of permafrost extent and active layer depth to soil and air temperatures and snow cover (e.g. Koven et al. 2013), using site-scale measurements of the active layer depth (CALM network) and vertically resolved temperature trends in boreholes. Consequences for the simulation of the terrestrial C reservoir and turnover will be evaluated using the new global C stock data from task 2.1.1. Methane emissions will be compared against site-wise flux observations, focusing on spatial and temporal variability (e.g. seasonal dynamics). Variations in modelled and observed methane emissions will be connected to changes in environmental variables (e.g. temperature, precipitation and soil water, Olefeldt et al. 2013). Wetland area and CH_4 emissions will be compared on regional and global scales following the WETCHIMP approach (Melton et al. 2013), as well as utilising CH_4 measurements and inversion products.

Task 2.1.3: Evaluating land cover and land-use effects in ESMs (ETH, CCMC, ENEA, ISAC, MPG, CNRS-IPSL)

We will derive new metrics to assess ESM spatial and temporal trends in land and vegetation cover resulting from improved representation of land-use change and vegetation dynamics. New multi-decadal ESA CCI land cover data will be used to define the adequacy of simulated trends in geographical and climatic spaces. In addition, two global leaf area index (LAI) satellite products (GIMMS-NDVI3g and GEOLAND-2) will be used to assess the ability of ESMs to reproduce spatial and inter-annual variations, as well as trends in vegetation phenology. Task 2.1.3 further serves to quantify improvements made in Task 1.1.3 in terms of the agreement between model and observed surface albedo, evapotranspiration and atmospheric coupling. Analysis will rely on both ground observations from FLUXNET, and satellite observations (GlobAlbedo and WACMOS ET). .

Deliverables

D2.1.1 Report on process-level evaluation of terrestrial improvements in European ESMs. (M60)

Milestones
M2.1.1. Report on data and model output requirements needed for evaluation (M6)
M2.1.2 Framework for evaluating offline simulations made in WP1.1 available (M18)
M2.1.3 Initial set of terrestrial biogeochemical metrics available to RT3 ESMValTool (M20)
M2.1.4. Process-evaluation of the initial model simulations and feedback to RT 1 (M30)
M2.1.5 Complete set of terrestrial biogeochemical metrics delivered to the ESMValTool repository (M52)
M2.1.6 Process-evaluation of the improved model simulations and feedback to RT 1 (M54)

Work package number	2.2	**Start Date or Starting Event**			Month 1-60		
Work package title	Evaluating marine processes in ESMs						
Participant number	21	14	3	2	13	17	10	4
Short name of participant	NOC	UEA	MPG	CNRS-IPSL	MF-CNRM	UiB	SMHI	CMCC
Person/months per participant	10	11	16	12	10	16	3	16

Objectives
This WP will compare simulated marine biogeochemistry of importance for climatic impacts and feedbacks with relevant observations. The WP has been designed to be an integral part of the development cycle of marine biogeochemical models. It will perform an evaluation of improved marine biogeochemical processes across a hierarchy of configurations, including offline, forced (interfaced with OCMIP) and coupled mode (results of full ESM simulations) and feed results back to WP1.2 in order to guide further model development. Finally, we will develop new skill-assessment metrics for both global and regional improvements in marine biogeochemistry. Suitable new top-down and key process-oriented diagnostics and performance metrics will be integrated into ESMValTool.

Description of work
Task 2.2.1 – Global-scale assessment of improved marine biogeochemistry (<u>NOC</u>, CNRS-IPSL, MPG, NOC, UEA, UiB, SMHI, CMCC)
This task performs a global evaluation of improved ocean physics and marine biogeochemistry developed in WP1.2. Attention will be paid to end-chain products of ESM biogeochemical modules that are essential in determining the amplitude of climate-biogeochemical feedbacks: marine biology, carbon export, air-sea exchanges of CO_2, N_2O, DMS, CO and isoprene. Advanced skill-assessment metrics (Stow et al., 2009) will be used to assess simulated distributions of biogeochemical fields. Marine production, carbon export and phytoplankton phenology will be evaluated with available databases from the MAREDAT initiative and satellite-derived observations (e.g., OC-CCI, CALIOP, ESA CMUG). Air-sea exchanges of greenhouse gases (CO_2, N_2O) and biogenic species developed in WP1.2.3 (DMS, CO and isoprene) will be evaluated against LDEO or SOCAT data for carbon fluxes and pCO_2, MEMENTO for N_2O fluxes, as well as SOLAS products for DMS, CO and isoprene. Skill-assessment protocols will be complemented with (1) process-based evaluation to investigate potential errors from physical drivers (e.g., mixed-layer depth) to biogeochemical fields (Séférian et al., 2013a), and (2) property-property evaluation to characterize the realism of simulated marine biogeochemistry as a function of atmospheric deposition of nutrients (Schlosser et al., 2013).

Task 2.2.2 – Regional-scale assessment of deep convection & upwelling system, oxygen minimum zone and coastal shelves (<u>CMCC</u> , UEA, CNRS-IPSL, UiB)
This task focuses on regional systems that are poorly represented in current generation ESMs (Cocco et al. 2013; Andrews et al., 2013): e.g. deep convection/upwelling regions, oxygen minimum zones (OMZ) and coastal shelves, which may improve through increased model resolution. Skill-assessment metrics will be developed to evaluate local/regional-scale processes influenced by (1) vertical or lateral movements of water in response to improved ocean physics (WP1.2.1) and (2) explicit representation of organic matter life cycle or atmospheric and riverine inputs (WP1.2.2 and WP1.2.3). Coastal systems will be assessed with coastal data compilations (e.g., Chen et al., 2013 or SOCAT, MEMENTO). The analyses of OMZs will rely on biases-corrected products (e.g., Bianchi et al., 2011) and focus on biogeochemical variables most relevant to the N_2O cycle. Deep convection/upwelling systems will be evaluated in term of carbon and oxygen

vertical distributions. Analyses will be completed with property-based diagnostics (e.g., water-masses (Iudicone et al., 2011)) or attribution methods (Séférian et al., 2013b) to understand systematic biases or missing processes in simulated biogeochemical fields.

Task 2.2.3 – Assessing variability, drift and trends of relevant biogeochemical fields (MF-CNRM, MPI, UiB, CMCC, UEA, CNRS-IPSL)
This task analyses how advances in ocean physics or in biogeochemical process description improves simulated biogeochemical processes on seasonal to multi-decadal timescales. Attention will be paid to air-sea exchanges of CO_2, N_2O and ocean-interior distribution of carbon-related fields and O_2. Application of existing multivariate index (e.g., Anav et al., 2013) and the development of new skill-assessment metrics (e.g. sensitivity to model equilibration protocols) e.g. model simulations versus available long-term datasets (e.g., SOCATv3 or WOCE), observational-derived statistical reconstructions (Majkut et al., 2014), inversions (Roedenbeck et al., 2014) or reanalyses (e.g., GLORYS, ERAClim2) will help quantify the realism of simulated marine biogeochemistry. These analyses will be complemented by property-based metrics establishing links between biogeochemical and physical fields, (e.g mixed layer depth), sea surface temperature (Tjiputra et al., 2014), ocean heat uptake (Bopp, 2002) or climate indices such as the NAO or SAM.

Deliverables (brief description and month of delivery)
D2.2.1 Report on process-level evaluation of marine improvements in European ESMs (M60)
Milestones
M2.2.1. Report on data and model output requirements needed for evaluation tests (M6)
M2.2.2 Framework for evaluating offline simulations made in WP1.2 available (M18)
M2.2.3 Initial set of marine biogeochemical metrics available for ESMValTool (M20)
M2.2.4 Process evaluation of initial model simulations and feedback to RT1 (M30)
M2.2.5 Complete set of marine biogeochemical metrics delivered to the ESMValTool code repository (M52)
M2.2.6 Process evaluation of improved model simulations and feedback to RT1 (M54)

Work package number	2.3	**Start Date or Starting Event**					Month 1-60
Work package title	Evaluating Natural Aerosol and Trace Gas Processes						
Participant number	1	5	9	13	8	2	19	24
Short name of participant	UNIVLEEDS	MOHC	METNO	MF-CNRM	KNMI	CNRS-IPSL	ULUND	FMI
Person/months per participant	24	18	10	13	10	10	4	6 (in-kind)

Objectives
This WP will evaluate natural aerosol and trace gas processes in ESMs, including the development of new metrics and evaluation tools. There are three main aims: (i) evaluate model aerosol state and variability generated by new Earth system couplings developed in WP1.3; (ii) assess the ability of models to simulate the pristine (baseline) aerosol and chemistry state uner conditions that represent as closely as possible the pre-industrial era; (iii) assess the ability of models to capture variability in natural aerosols and trace gases driven by variations in natural processes. Evaluation will focus on emissions and atmospheric processing of natural aerosols (sea spray, dust, wildfire carbonaceous particles, DMS, secondary organic aerosol from terrestrial biogenic emissions) and trace gases (methane and carbon dioxide). Suitable top-down and key process-oriented diagnostics and performance metrics for evaluating natural aerosol and trace gas processes in ESMs will be integrated into ESMValTool.

Description of work
Task 2.3.1. Evaluation of new ESM coupled aerosol processes (METNO, UNIVLEEDS, CNRS-IPSL, MOHC, KNMI, ULUND, FMI)
This task focuses on evaluation of specific aerosol species and sources that are predicted by the newly

developed coupled processes in the ESMs.

Dust and iron deposition*:* Soluble iron is a limiting nutrient for phytoplankton in High Nutrient, Low Chlorophyll regions. Several models are developing parameterisations to compute soluble iron in a physical way. Recent databases of global dust properties (Sholkovitz et al., 2012) will be used to evaluate if models correctly represent the distribution of dust and soluble iron in the atmosphere and ocean. CNRS-IPSL will provide iron content of dust emissions as a function of geographical location based upon Journet et al. (2014). Dust deposition from all models with an interactive dust cycle will be evaluated using a database of several hundred measurements assembled by CNRS-IPSL.

Biogenic organic aerosol*:* New models of biogenic VOC emissions coupled to land surface schemes and driven by climate variables will be evaluated against a global database of Aerosol Mass Spectrometer (AMS) measurements (Spracklen et al., 2011).

Wildfire occurrence and aerosol: Wildfire aerosol emissions will be coupled to land surface models in some ESMs. Where possible, participating models will first be assessed using offline/uncoupled simulations to determine model performance in terms of simulated burned area and burn intensity and the results compared to data in the Global Fire Emissions Database (GFED3). The evaluation of emissions will emphasize spatial, seasonal and interannual variability and plume height through MISR plume products, CALIOP extinction profiles, constrained by AOD estimates from satellites and Aeronet.

Marine aerosol: New treatments of coupled biological models predicting DMS emissions will be tested using DMS and MSA measurements from remote regions (e.g., from Amsterdam Island) and vertical distribution of sulphate from selected aircraft measurements. These will be complemented by CCN measurements at Cape Grim. Evaluation will focus on seasonal and interannual variability, with model experiments designed to separate biological and physical drivers.

Task 2.3.2. Evaluation of aerosol under pre-industrial-like natural conditions (UNIVLEEDS)

A major difficulty in the evaluation of modelled natural aerosol is that observed aerosol is almost always a mixture of natural and anthropogenic components. Although some components can easily be separated (e.g. salt from natural sea spray), this is not the case for particle number concentrations, which determine CCN and effects on clouds. The aim of this task is to therefore to evaluate ESMs under conditions identified to be as pristine as possible, in which aerosol properties are dominated by natural processes. This is a challenge because almost all northern hemisphere regions are strongly affected by anthropogenic emissions and most southern hemisphere regions are marine. A combination of metrics will be tested in one ESM (UKESM1) to define pristine regions based on trace gases (e.g., CO), black carbon aerosol, similarity of pre-industrial and present day aerosol, and aerosol responses to perturbations. An optimum metric will be developed that can be applied to the full set of ESMs, and which can be incorporated in the ESMVal tool as a routine benchmark of model performance under close-to pre-industrial conditions

We will use in situ aerosol property measurements from the Global Aerosol Synthesis and Science (GASSP) project together with satellite aerosol optical depth and Angstrom coefficient data. Comparison of models will be made to understand how the complexity of aerosol schemes in the ESMs affects their skill against measurements. In particular, we will assess how the inclusion of microphysical processes affects the sensitivity of the modelled aerosol to changes in natural emissions. The quantified uncertainty/diversity in the multi-model pristine aerosol state will be used in Task 3.3.3 to evaluate the effect of uncertain pre-industrial baseline aerosol on historical changes in aerosol radiative forcing and climate response.

Task 2.3.3. Evaluation of trace gases (MOHC, CNRS-IPSL, KNMI).

This task will assess the performance of interactive emission schemes, deposition fluxes, and the impact of interactive emissions on trace gas model performance. New BVOC emission schemes coupled to ESM land surface schemes will be compared to surface flux measurements, focussing on the diurnal cycle, day-to-day variability, and seasonal cycle. Runs will be a mixture of offline land surface model runs forced by reanalyses, online runs with prescribed vegetation, and/or online runs with interactive vegetation. In addition, a number of future timeslice runs will be made to evaluate how BVOC emissions respond to changes in temperature, CO_2, and vegetation. The impact of interactive BVOC emissions (WP1.3) and CH_4 wetland emissions (WP1.1) on tropospheric ozone and CH_4 lifetime will be quantified.

Given the role of reactive nitrogen in the strength of the land carbon sink and marine biology, this task will evaluate deposition fluxes of NO_y and NH_x using site-level observations from the World Data Centre for

Precipitation Chemistry. The evaluation will also benchmark the projects ESMs against the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) multi-model ensemble dataset. Past and future changes will be assessed by performing a number of historical and future timeslice experiments and again, comparing to ACCMIP.

Top-down trace-gas evaluation builds on earlier work on the development of the, ESMValTool. The focus will be on tropospheric ozone, its precursors including methane, and stratospheric ozone. In particular, we will extend the observational datasets and performance metrics currently available in ESMValTool (e.g. comparisons with multi-model ensembles such as ACCMIP, CCMVal2, and CCMI; comparisons with appropriate satellite products such as TES). MOHC will apply ESMValTool to evaluate its own simulations of the JULES model (with interactive wetland, fire, and BVOC emissions) coupled to HadGEM3/UKESM and those of the other ESMs.

T2.3.4. Carbon dioxide evaluation (CNRM).
We will evaluate the distribution of atmospheric CO_2 from the CMIP DECK historical simulations against (1) satellite-derived observations (GOSAT, AIRS, IASI and the OCO-2 ESA ECV) as well as ground-based measurements (GAW, ICOS and TCCON networks). Priority will be given to assess variability and trends from seasonal to decadal timescales. Process-based evaluation will be conducted to established links between atmospheric CO_2 and physical and biogeochemical drivers (Ciais et al., 2013b). The process-based metrics will feedback to developments in RT1 and be employed as baseline for the development of emergent constraints in RT3.

Deliverables (brief description and month of delivery)
D2.3.1 Report on process-level evaluation of aerosol and trace gas improvements in European ESMs. (M60)
Milestones
M2.3.1. Report on data and model output requirements needed for evaluation tests (M6)
M2.3.2 Framework for evaluating offline simulations made in WP1.3 available (M18)
M2.3.3 Initial set of aerosol and trace gas metrics available for ESMValTool (M20)
M2.3.4. Process evaluation of initial model simulations and feedback to RT1 (M30)
M2.3.5 Complete set of aerosol and trace gas metrics available for ESMValTool (M52)
M2.3.6 Process evaluation of improved model simulations and feedback to RT1 (M54)

Work package number	3.1	**Start Date or Starting Event**				Month 1-60
Work package title	Towards routine benchmarking of ESMs					
Participant number	6	10	3	7	16	11	12
Short name of participant	UNEXE	SMHI	MPG	DLR	ETH	UREAD	ENEA
Person/months per participant	8	22	14	32	15	19	12

Objectives
This WP will develop an ESM evaluation and benchmarking tool that produces well-established analyses as soon as model results become available. In addition, it will provide support for the integration of diagnostics and emergent constraints developed in RT2 and RT3. The tool will be used to evaluate CMIP DECK simulations made by the project ESMs and for operational analysis of future projections. The resulting tool will be made openly available to the international research community.
The individual objectives of the WP are to:

- Further develop an ESM benchmarking and evaluation tool (ESMValTool), making use of observations from projects such as ESA CCI and Obs4MIPs, extending the physical climate to include key biogeochemical diagnostics;
- Extend ESMValTool with new diagnostics for operational analysis of multi-model ESM projections;.
- Provide user guidelines for other partners to include new diagnostics and performance metrics for process-based model evaluation (RT2) and emergent constraints (WP3.2) into ESMValTool;

- Provide documentation on how to use ESMValTool and release the tool into the public domain.

Description of work

Task 3.1.1 Enhanced platform for routine evaluation and benchmarking of ESMs (DLR, SMHI, MPG, ETH, UNEXE,UREAD)

This task will develop a benchmarking and evaluation tool that produces well-established analyses as soon as model results become available (i.e. quasi-operational evaluation). To reach this, we will extend work performed in the project EMBRACE by introducing new important Essential Climate Variables (ECVs) and standard diagnostics not yet covered in ESMValTool. We will take advantage of new observations available through initiatives such as the ESA CCI and Obs4MIP. New diagnostics will cover the following 3 areas; (i) key aspects of physical climate performance not already implemented in ESMValTool (e.g. surface radiation, turbulent energy and water fluxes); (ii) measures of the physical climate which play a critical role in determining the fidelity of the Earth system components targeted for improvement in the project (e.g. precipitation variability, soil hydrology and the terrestrial carbon cycle, ocean mixed-layer depth, ocean stratification and the marine carbon cycle, cloud processes and aerosol-radiation interactions) and (iii) key performance measures for the actual target biogeochemical and aerosol processes in the ESMs. The latter performance measures will consider interactions between physical climate and biogeochemical variability on a range of timescales. We will also implement a set of standard diagnostics facilitating routine and traceable multi-model intercomparison, such as selected diagnostics from the evaluation chapter of IPCC AR5 (Chapter 9, Flato et al., 2014). In addition, the tool will extended to allow easy analysis and intercomparison between multi-model future projections, with standard diagnostic plots such as from the projection chapter of IPCC AR5 (Chapter 12, Collins et al., 2014). Finally, we will work to develop interfaces to existing diagnostic packages e.g. the PCMDI metrics package, the NCAR diagnostic packages and the UK Met Office Auto-Assess package.

The enhanced version of ESMValTool will be used for a comprehensive evaluation of the CMIP DECK experiments, with results made available to RT1 to support further ESM process improvements. Results will also provide measures of uncertainty in CMIP DECK and scenario simulations for RT4.

Task 3.1.2 Maintenance, Technical Infrastructure, Interfaces, and Documentation (SMHI, DLR, ENEA, MPG, UREAD)

In this Task we will ensure a proper maintenance, technical infrastructure, interfaces, and overall documentation of the ESMValTool throughout the project. A version controlled repository will be made available by DLR for community based development. In addition, DLR will maintain a web based project management tool for issue tracking and documentation of ESMValTool. The task will further work on technical improvements of the tool including a web-interface to visualize the results and provide a comprehensive testing suite to ensure high quality and reproducible results. We will provide technical support to other project partners who will implement diagnostics into ESMValTool as part of RT2 (process evaluation), and RT3.2 (emergent constraints). In addition, the ESMValTool core development team (DLR, MPI, and SMHI) will be responsible for maintaining a stable version of the tool in the trunk including quality control and testing so that all routines are technically implemented correctly. UREAD will couple the ESMValTool to the infrastructure of the ESGF in collaboration with the ExArch project. This will allow ESMValTool to run operationally alongside selected ESGF data nodes (e.g., BADC, DKRZ, PCMDI) so CMIP DECK / CMIP6 simulations can be routinely evaluated and inter-compared.

Deliverables

D3.1.1: Benchmarking of CMIP DECK runs made by project ESMs (M38)
D3.1.2 ESMValTool 2.0 release (M60)

Milestones

M3.1.1: ESMValTool prototype implementation on selected ESGF nodes (M18)
M3.1.2: ESMValTool with new diagnostics (M24)
M3.1.3: ESMValTool (internal) release for CMIP DECK evaluation (M32)
M3.1.4: Consolidated software release, including all diagnostics, for internal verification (M56)

Work package number	3.2	Start Date or Starting Event					Month 1-60		
Work package title	Understanding and constraining model projections								
Participant number	6	16	7	15	1	14	5	2	3	17
Short name of participant	UNEXE	ETH	DLR	UHAM	UNIVLEEDS	UEA	MOHC	CNRS-IPSL	MPG	UiB
Person/months per participant	36	36	29	29	21	11	12	10	10	5

Objectives

This WP will develop and apply techniques to evaluate and weight model projections based on aspects of the current climate that matter most for future projections. Ensembles of Earth System (ES) projections will be utilised to identify **robust** relationships evident across models, between key aspects of future projections and observable features of the current Earth System. In combination with observations, such relationships provide *Emergent Constraints* on the key aspects of future projections, that we will use to weight projections and focus future model development.

Emergent Constraints have been identified for physical climate feedbacks such as snow-albedo feedbacks (Hall and Qu, 2007), land carbon cycle feedbacks (Cox et al., 2013), and equilibrium climate sensitivity to doubling CO_2 (Fasullo and Trenberth, 2012). Given the increasingly large archive of model outputs, there are risks associated with indiscriminate data-mining that can lead to the identification of spurious relationships between aspects of the current climate simulations and future projections (Caldwell et al., 2014). Similarly there is a risk of failing to identify emergent constraints if the selection of the long-term and short-term variables to be correlated is not based-on a thorough understanding of the processes that link them (Wang et al., 2014a). We will deal with these risks by building our search for Emergent Constraints on a sound physical/biogeochemical understanding and rigorous approaches used in statistical physics, such as the Fluctuation-Dissipation Theorem (FDT) and linear response theory (Lucarini and Sarno, 2011). These firm foundations will guide the search for emergent constraints on future projection uncertainties. The objective is to identify a suite of features of the current climate that are most relevant for the fidelity of future projections.

Description of work

Task 3.2.1: Theoretical foundations for emergent constraints (<u>UHAM</u>, UNEXE)

The climate provides a clear example of a forced dissipative system, far from equilibrium, featuring instabilities, a limited predictability horizon, and multi-scale properties (Lucarini, 2014). However, it is possible in principle to use the natural fluctuations of the system to construct approximate response operators that link the sensitivity of climate to external forcing to its internal variability (Leith, 1975), in the spirit of the Fluctuation-Dissipation Theorem (FDT). Recent advances in statistical mechanics provide methods to predict the climate response at any lead-time, by linking short to long time scales (Lucarini & Sarno, 2011). This task will connect these methods to the concept of Emergent Constraints, providing theoretical insight on the variables and variability in current climate most connected to key aspects of future climate evolution, guiding the search for, and analysis of, Emergent Constraints in the rest of the WP.

Task 3.2.2: Emergent constraints on physical and biophysical feedbacks (<u>ETH</u>, DLR)

Physical feedbacks that determine climate sensitivity and the transient climate response interact with the target Earth System feedbacks of this proposal. To constrain the overall transient climate response to carbon emissions (TCRE) we will continue existing work to constrain sea ice, snow albedo, and cloud feedbacks. In addition, new targets will include soil moisture-atmosphere feedbacks and biophysical effects of land use and land cover variations – with the aim of reducing uncertainty in projections of land temperature and hydrological extremes. The task will evaluate to what degree constraints are robust across different ensembles (Perturbed Parameter Ensembles (PPE) and multi-model), and how they change over time or as a function of climate state, to provide a coherent view of the climate response at all lead times.

Task 3.2.3: Emergent constraints on land carbon cycle feedbacks (UNEXE, DLR, CNRS-IPSL, MOHC)
An emergent linear relationship, between the long-term sensitivity of tropical land carbon storage to climate warming and the interannual variability of atmospheric CO_2, has previously been identified across an ensemble of ESMs participating in C^4MIP (Cox et al., 2013) and more recently in CMIP5 models (Wenzel et al., 2014). This task will investigate possible additional constraints on climate-carbon cycle feedbacks, guided by the theoretical underpinnings from Task 3.2.1, and making use of observed trends in the seasonal cycle (Graven et al., 2013) and interannual variability of CO_2 (Wang et al., 2014b), as well as satellite derived patterns of vegetation greenness and Gross Primary Productivity (GPP). The objective is to identify key aspects of present-day land carbon cycle variability most relevant to future climate-carbon cycle projections, and thus prioritize ESM evaluation and model development.

Task 3.2.4: Emergent constraints on ocean carbon cycle feedbacks (UEA, CNRS-IPSL, MPG, UiB)
Emergent relationships between biogeochemical ocean tracers have long been used to constrain marine carbon. Inventories of $\delta^{14}C$ (Orr et al., 2001) and CFCs (Matsumoto et al., 2004) were used in the first phase of OCMIP, to constrain carbon storage in the Southern Ocean in response to increasing atmospheric CO_2. But emergent relationships to constrain the impact of climate change on marine sources and sinks of carbon have not been explored in the past, yet there is much potential to do so. In this task, we will use observational estimates of Total Alkalinity (TA), Total CO_2 (TCO2), Sea-Surface Temperature (SST) and Sea-Surface Salinity (SSS) to separate the effects of CO_2 increase and climate change on the ocean carbon cycle and identify Emergent Constraints on future carbon uptake. Each of these variables respond differently to climate and CO_2 (Ilyina and Zeebe, 2012). By analyzing the co-evolution of TA, TCO2, SSS and SST we aim to constrain both the ocean carbon-climate and carbon-concentration feedbacks.

Task 3.2.5 Emergent constraints on aerosols and trace gases (UNIVLEEDS, DLR)
Emissions of important natural aerosols such as wildfire and dust are strongly coupled to the physical climate (e.g., temperature, surface moisture, wind speed). This task aims to constrain the climate-driven response of these emissions by analyzing multi-model ensembles and relevant measurements . It is well known that forest fires in some regions have strong interannual variability that is correlated with certain climate variables (Rupp et al. 2007) Observationally constrained ensemble projections will be compared against unconstrained projections to narrow the uncertainty in long term changes in wildfires and dust. Another positive climate feedback may be introduced through a projected increase in the Brewer-Dobson circulation in a warmer climate leading to an increase in the flux of ozone from the stratosphere to the troposphere (Neu et al., 2014) and a decrease of tropical ozone in the lower stratosphere (Eyring et al., 2013). Interannual and seasonal variations will be explored from project models with interactive chemistry and used to study emergent constraints for the climate-driven response of ozone feedbacks.

Task 3.2.6 Weighting ensembles of multi-model Earth system projections (DLR, ETH)
While considerable progress has been made in developing model evaluation and performance metrics, the ESM community has fallen short of providing ensemble projections of future climate that go beyond 'model democracy' (i.e. treating all models as equally likely to be true). In part, this is because metrics used to evaluate model simulations of the current climate have rarely been shown to be relevant to details of future projections. Model evaluation therefore currently has a subjective element associated with the variables selected to compare to observations, and is often dubbed a 'beauty contest'. Emergent Constraints provide a means to advance significantly beyond this current state, as they identify aspects of current climate that are most relevant for future projections. This task will develop methods to more objectively weight projections based-on Emergent Constraints, and to quantify uncertainties in the resulting ensemble projections taking into account both model performance and model interdependence. The results will be valuable for guiding the design of future ensembles, e.g., *how many* and *what* models are needed to maximize information at minimal computational cost.

Deliverables
D3.2.1 Paper on the theoretical basis for emergent constraints (M30)
D3.2.2 Synthesis Report on new emergent constraints and the key aspects of current climate that determine the fidelity of climate projections (M60)
D3.2.3 Report on the weighting of CMIP6/CRESCENDO projections (M60)

Milestones
M3.2.1 Initial analysis of CMIP5 models for previously identified Emergent Constraints (M12) M3.2.2 Initial theoretical guidance on the links between the nature of current variability and Earth system sensitivity (M18) M3.2.3 First workshop: Emergent Constraints – in theory and in CMIP5 models (M24) M3.2.4 Exploration of new Emergent Constraints on physical, biophysical, carbon cycle and aerosol feedbacks in CMIP5 models (M36) M3.2.5 Exploration of Emergent Constraints in CRESCENDO/CMIP6 runs and comparison to CMIP5 (M54) M3.2.6 Second workshop: Emergent Constraints – robustness across model generations (M54)

Work package number	3.3	**Start Date or Starting Event**				Month 18-60			
Work package title	Quantification of forcing and feedbacks								
Participant number	11	1	9	2	13	5	22	7	3
Short name of participant	UREAD	UNIVLEEDS	METNO	CNRS-IPSL	MF-CNRM	MOHC	CNR	DLR	MPG
Person/months per participant	24	7	9	9	2	2	2	8	2

Objectives

This WP will use a combination of transient (coupled ocean-atmosphere) and timeslice (fixed SST) experiments to consistently quantify forcings, feedbacks and climate response across different ESM simulations and different components of the Earth system This extends earlier work on carbon cycle feedbacks to other biogeochemical feedbacks; e.g. carbon dioxide, methane, ozone, sulphate, nitrate, dust, sea salt, as well as emissions of; wetland and permafrost methane, biomass burning (aerosol and ozone precursors), DMS and BVOCs. The three quantities needed to calculate the feedbacks are the radiative efficiencies (phi), interactions between atmospheric constituents (beta) and sensitivities to climate change (gamma), see Gregory et al 2009 for more details). WP Objectives include: (i) Quantification of natural and anthropogenic ERF including biogeochemical interactions (phi and beta). (ii) Quantification of sensitivities to climate (gamma). (iii) Calculation of climate feedbacks from phi, beta and gamma. (iv) Quantification of climate response to aerosols and ozone. To facilitate future calculation of forcings and feedbacks diagnostics developed in the WP will be implemented in ESMValTool.

Description of work

T3.3.1 ERF and biogeochemical coupling experiments (METNO, CNRS-IPSL, MOHC, MF-CNRM, ISAC)

In this task ESMs with interactive chemistry will conduct timeslice experiments with fixed SSTs to calculate top-of-atmosphere and surface ERFs. Global perturbations will be carried out separately for the following species/emissions in ESMs that include the target species/process: CH_4, N_2O, and CFC/HCFC concentrations, emissions of anthropogenic aerosol and ozone precursors, emissions of dust, sea salt, DMS and BVOCs and, for certain models, biomass burning emissions. For well-mixed GHGs and other anthropogenic pollutants, perturbations will be for the year 2015 minus pre-industrial conditions. For natural emissions (dust, sea salt, biomass burning, DMS, BVOC) these will be imposed as a doubling of pre-industrial (natural) emissions. When modelled interactively, land use change will also have consequences for natural emissions.

Although well-mixed GHGs are prescribed as concentration changes, the other chemical species (ozone, stratospheric H_2O, aerosols) will respond to the perturbed state. For the short-lived anthropogenic pollutants (BC, CO, NO_X, NH_3, OC, SO_2, VOC) simulations will be carried out twice, first with only aerosols coupled to the radiation scheme, and second with only ozone coupled to radiation (with biogeochemical couplings remaining active in both). This will allow separation of ERF from ozone and from aerosol changes. Simulations will be 5 years for models that can nudge winds to analyses, or 30 years for those that cannot. The *phi* coefficients will be calculated from the ratio of ERF to concentration change. The *beta* coefficients from the responses of one species to the concentration change in another. For models that are able, a triple call to the radiation scheme will be used to quantify direct and indirect radiative forcing

These experiments are coordinated with AerChemMIP, LUMIP and the Radiative Forcing Model Intercomparison Project (RFMIP).

Species	Perturbation	MIP
Control	1850 land use, emissions and concentration	DECK control
Land Use	2015 Land use	LUMIP
CH4	2015 CH_4 concentration	RFMIP
N2O	2015 N_2O concentration	RFMIP
CFC, HCFC	2015 (H)CFC concentrations	RFMIP
BC, CO, NO_X, NH_3, OC, SO_2, VOC	2015 emissions, coupled aerosol coupled O_3	AerChemMIP AerChemMIP
Dust	2xPI emissions	AerChemMIP
Sea salt	2xPI emissions	AerChemMIP
DMS	2xPI emissions	AerChemMIP
Biomass burning	2xPI emissions	AerChemMIP
BVOC	2xPI emissions	AerChemMIP

T3.3.2 Feedback framework and calculation (**UREAD**)
Data from the T3.3.1 with ERF experiments along with data from C^4MIP (for sensitivity to climate, and to CO_2) will be analysed following the framework of Gregory et al. (2009) to calculate the coefficients (*beta, gamma and phi*) and overall biogeochemical feedbacks for each of the climate processes. As an example changing temperature could change natural methane emissions and hence concentrations (*gamma*) which affect radiative forcing (*phi*) and through atmospheric chemistry affect sulphate aerosol burdens (*beta*). Outputs will include global temperature responses and fast and slow precipitation responses.

For an intercomparison of feedbacks across different ESMs it is essential to quantify them consistently. We propose a matrix formulation to facilitate the comparison of Earth system feedbacks with each other and across models. This will serve as a tool for ESM intercomparison, making this WP a multi-model activity. Earlier work by Gregory et al. (2009) has shown how the climate-carbon and the concentration-carbon feedback can be expressed in formally similar ways, such that their magnitudes can be compared. This is a formal methodology for quantifying the change that results in each of various "output" (climate, concentrations of constituents) given the "input" (emissions). The usefulness of the framework is that it allows the importance and uncertainty of Earth system processes to be compared within and across ESMs in common terms. Collins et al. (manuscript in preparation) suggests this can be expanded to other biogeochemical feedbacks. Here we include CO_2, CH_4, O_3, sulphate, nitrate, dust, sea salt, wetland and permafrost methane emissions, biomass burning, as well as DMS and BVOC emissions.

T3.3.3 Transient experiments (UNIVLEEDS, DLR, METNO, CNRS-IPSL, CCMC, MOHC, MPG, MF-CNRM, CNR)
Transient (coupled ocean-atmosphere) experiments are needed to understand regional climate responses to heterogeneous forcing changes. Comparison with the global linear formulation will help evaluate its applicability. The most important heterogeneous agents are tropospheric ozone, aerosols, and land use This task will consist of analysis of the DAMIP (Detection and Attribution MIP) GHG-only historical simulations covering the period 1850-2015 with extra simulations:
1) Historical simulation with fixed aerosol and ozone precursor emissions (natural and anthropogenic),
2) Historical simulation with time-varying natural but fixed anthropogenic aerosol and ozone precursor emissions. Two additional simulations with time-varying natural emissions spanning some of the uncertainty in these emissions
3) Historical simulations with time-varying natural and anthropogenic aerosol and ozone precursors (AerChemMIP)
3) historical simulation with varying land use only (DAMIP)

GHG concentrations will follow the historical observations. These will be compared with predictions generated for the ERF approach in T3.3.1 and climate response coefficients from Shindell and Faluvegi (2009) to assess the importance of regional heterogeneity in radiative forcing on regional climate change.

Deliverables (brief description and month of delivery)
D3.3.1 Report on the sensitivity of aerosol radiative forcing to improvements and uncertainty in the representation of the pre-industrial aerosol state (M52) D3.3.2 Report on the contribution of heterogeneous forcing agents to historical climate change (M54). D3.3.3 Report detailing the ERFs for natural and anthropogenic forcing agents in ESMs and the Climate feedback matrix (M60) **Milestones** M3.3.1 Climate feedback matrix framework available (M30) M3.3.2 ERF simulations completed (M40) M3.3.3 Transient simulations completed (M45)

Work package number	4.1	**Start Date or Starting Event**			Month 1-30		
Work package title	Novel climate scenarios and future projections: the CMIP6 Scenario MIP						
Participant number	18	23	20	16	5	7	6	8
Short name of participant	PBL	IIASA	PIK	ETH	MOHC	DLR	UNEXE	KNMI
Person/months per participant	30	30	22	6	6	3	3	9

Objectives

In CMIP5, the RCPs were used to explore climate change. In the coming years, new scenarios will be formulated that should be used by the ESM community as part of CMIP6. This WP focuses on the development of new scenarios of the drivers of climate change (e.g. socio-economic development, future trace gas and aerosols emissions and future land-use/land-cover). WP4.2 focuses on use of this data in generating an ensemble of ESM projections. This effort constitutes a major European contribution to the CMIP6 ScenarioMIP. Specific objectives are to:

- Develop improved methodologies on how socio-economic scenarios can best be developed to integrate knowledge on climate change, climate impacts, adaptation and mitigation.
- Improve information exchange between IAM and ESMs in support of Earth system projections.
- Contribute to the design and development of a new set of scenarios describing the range of possible future evolutions of emissions and land use as input to CMIP6 Earth system models.

Description of work

Task 4.1.1: Novel methods for populating and analysing the set of new scenarios (PBL, PIK, IIASA, ETH, MOHC, DLR, UNEXE, KNMI)

The current protocol for ScenarioMIP is based on selecting a limited set of scenarios, that together cover a range of different GHG forcing levels (high, medium and low), as well as a range of different socio-economic development pathways (e.g. uncertainties in future land use, aerosol emissions and mitigation overshoots). In the design process of ScenarioMIP, alternative methods have been proposed, including the use of pattern scaling and statistical sampling. This task aims to assess the strengths and weaknesses of different methods for scenario design and more specifically, whether the priority scenarioMIP scenarios fully sample the emission uncertainty space. In evaluating different options for scenario design, several factors need to be considered including 1) optimizing the limited ESM resources, 2) ensuring a useful level of signal-to-noise in the forced climate change (signal) relative to natural variability (noise), and 3) ensuring sufficient differences across the scenarios (e.g. concerning land use and aerosols). In this task we focus on a set of recommendations that can be used in future scenario design as well as in setting priorities within the larger set of CMIP6 scenarios.

Task 4.1.2: Development and design of a new data set of scenarios (PBL, PIK, IIASA)

Community scenarios, such as ScenarioMIP, need to be developed using IAM models. During 2012-2014, five IAM teams developed a new set of socio-economic scenarios called the SSPs that form the basis of the ScenarioMIP selection (3 of these teams – IMAGE, MESSAGE and REMIND - are part of CRESCENDO). These scenarios are based on the new matrix approach to climate research (Van Vuuren et al. 2013) and constitute an initial contribution to ScenarioMIP. In this task we focus on making the IAM output suitable for driving ESMs. For the RCPs, methods were developed to provide information on future emissions of GHGs, air pollutants and land use to the ESM community. These methods: 1) ensure consistent data for the historical and future periods, 2) harmonize the base year across different IAMs and 3) provide data on geographical grids relevant to ESMs. In this task updated methods will be applied to make the IAM output of the SSPs suitable as input to ESMs. It is envisioned that some new variables will also be added in the data exchange between IAM and ESM models (e.g. more detailed data on land cover and gridded/source specific CO_2 emission data). For this task, the IAM teams in CRESCENDO will work with other key partners through ScenarioMIP, with the aim of developing a useable set of new scenarios for CMIP6 ESMs.

Task 4.1.3: Testing new scenarios with ESMs (**MOHC**, **KNMI**)
In the design of new scenarios in task 4.1.2 a number of open questions related to climate change responses in the ESMs to (relatively small) differences in forcing data – i.e. in particular land use patterns, aerosol emissions (over time and space) and climate forcing - need to be addressed. To reduce the risk of poor scenario design propagating into the full CMIP6 activity a small set of preliminary scenarios will be tested with a 1 or 2 project ESMs. Findings from these tests will provide useful guidance on the development and implementation of scenario experiments, such as ScenarioMIP.

Deliverables (brief description and month of delivery)
D4.1.1: Report describing the new IAM scenarios as part of the CMIP6 ScenarioMIP data. (M30)
Milestones
M.4.1.1: Report assessing the level of uncertainty space sampled by the ScenarioMIP tier 1 scenarios compared to the full range of CMIP6 scenario forcing uncertainties. (M20).
M.4.1.2: Final delivery of a set of new scenarios as part of the CMIP6 ScenarioMIP (M24)
M.4.1.3: Evaluation report on preliminary ESM testing of CMIP6 scenarios (M24).

Work package number	4.2		**Start Date or Starting Event**			Month 1-36			
Work package title	Assessing the robustness of ESM performance and projection response to model resolution									
Participant number	11	10	1	3	21	2	13	9	5	4
Short name of participant	UREAD	SMHI	UNIVLEEDS	MPG	NOC	CNRS-IPSL	MF-CNRM	METNO	MOHC	CMCC
Person/months per participant	19	12	6	3	8	3	3	10	6	3

Objectives
In this WP we will establish the performance and projection traceability of standard (CMIP6) resolution ESMs compared to lower resolution equivalent versions of the same models. This to aid in efficiently sampling a matrix of future emission scenarios (WP4.1 and ScenarioMIP), by state of the art ESMs.

Description of work
WP4.1 will contribute to the development of new emission and land use scenarios for CMIP6. As well as considering high-medium-low GHG forcing these will also consider aspects such as; land use/land cover changes and potential variations in future emissions of non-greenhouse gases and aerosols. Sampling the resulting set of scenarios with a sufficiently large multi-model, multi-member ensemble will be a major challenge for the ESM community. A range of methods for efficiently sampling these scenarios will be investigated in WP4.1. One option, explored in this WP, is to use in addition to a small number of standard (CMIP6) resolution ESMs, a set of lower resolution, computationally efficient, ESMs based directly on the standard CMIP6 models. This approach requires that the lower resolution models reproduce the simulation quality and future projection response of the standard resolution (parent) models to an acceptable degree. The aim of the WP is to explore and document this traceability and use this to inform strategies for

sampling CMIP6 and other community scenarios

CRESCENDO ESMs will carry out CMIP DECK simulations with their standard (CMIP6) models in the first half of the project. The robustness of simulated processes, future projections and feedbacks, to varying ESM resolution will be assessed by running a subset of the CMIP DECK experiments with lower resolution ESMs. The low resolution ESMs will use a resolution similar to CMIP5 standard ESMs, and thus be ~8-10 times faster than equivalent CMIP6 resolution models, allowing a larger ensemble of simulations to be made.

The CMIP DECK simulations for each ESM resolution set will be analysed and where systematic differences are found the underlying processes causing these differences identified. Different responses to present and future forcing will be mapped and approaches sought to interpret low resolution members in the context of standard resolution members. Emphasis will be placed on both the reproducibility of observed (past) large-scale climate variability and trends, as well as future projection responses to changed external forcing. Analysis will consider both the physical climate and biogeochemical and aerosol responses. In particular we aim to establish the degree to which large scale future projection responses in the standard and low resolution ESMs are similar and at what spatial scales this similarity, if evident, breaks down.

Task 4.2.1 CMIP DECK simulations using low resolution ESMs (**UREAD, SMHI, MPG, CNRS-IPSL, CNRM, METNO, CMCC**)
Repeat a set of key CMIP DECK simulations using lower resolution version of CMIP6 ESMs. If changes in any ESM settings are required when moving from standard to low resolution, clearly document these changes.

Task 4.2.2: Traceability between low and standard resolution ESMs (**UREAD, SMHI, UNIVLEEDS, NOC, METNO, MOHC**)
Assess the traceability of ESM simulations to resolution assessing both the simulated present climate and responses to changing greenhouse forcing using CMIP DECK simulations. Results will inform the development and analysis of the ESM projections generated in WP4.2.

Deliverables (brief description and month of delivery)
D4.2.1: Report on the traceability of performance and future projection responses between low and standard resolution ESMs (M36).
Milestones
M4.2.1 Low resolution versions of ESMs run for a subset of CMIP DECK simulations (M30)
M4.2.2 Recommendations on the use of low and standard resolution ESMs for scenarioMIP (M32)

Work package number	4.3	**Start Date or Starting Event**						Month 24-60		
Work package title	Organising ESM simulations for CMIP6 ScenarioMIP									
Participant number	18	23	20	16	5	7	8	6	10	11	3
Short name of participant	PBL	IIASA	PIK	ETH	MOHC	DLR	KNMI	UNEXE	SMHI	UREAD	MPG
Person/months per participant	12	12	4	5	5	3	3	3	5	5	5
Participant number	13	22	4	17	2						
Short name of participant	MF-CNRM	CNR	CMCC	UiB	CNRS-IPSL						
Person/months per participant	5	5	5	5	5						

Objectives
This workpackage will coordinate a set of simulations with the project ESMs sampling an agreed set of CMIP6/ScenarioMIP scenarios developed in WP4.1. It will also perform an initial analysis and interpretation of the resulting ESM projection matrix in combination with the base IAM scenarios.

Description of work **Task 4.3.1: Coordinated ESM projections for ScenarioMIP (<u>SMHI</u>, UREAD, MPI, IPSK, CNRM, CNR, CMCC, UiB)** CRESCENDO ESMs will perform a set of projections sampling the new scenarios developed in WP4.1. A mix of standard resolution (*CMIP6*) and lower resolution (*typical in CMIP5*) versions of the project ESMs will be used, guided by findings in WP4.2 and international prioritization of the CMIP6 scenarios. This WP will coordinate a European ESM contribution to ScenarioMIP and other relevant community scenarios and through WP5.2 will ensure the resulting projections are saved on the ESGF and provided in a supported manner to the climate impacts (ISI-MIP) and regional climate downscaling (CORDEX) communities. **Task 4.3.2: Interpretation of ScenarioMIP results by multiple research communities (<u>PBL</u>, PIK, IIASA, ETH, MOHC, KNMI, DLR, SMHI and UEXE)** A full assessment of projected Earth system change, associated socio-economic impacts and possible adaptation-mitigation responses increasingly requires analysis by an inter-disciplinary set of research communities. An important reason for this is the complex relationship between human activities and Earth system change, including feedbacks of Earth system change onto human activities. In this task, we focus on such a joint interpretation, considering both ESM and IAM data arising from ScenarioMIP as well as other relevant MIP scenarios (e.g. possibly associated with mitigation overshoot, future land use or aerosol emission uncertainties). This will include; implications of land-use change for Earth system change, derivation of carbon budgets and implications for socio-economic development and interpretation of the implications of projected changes from the perspective of climate impacts and socio-economic response options. Collaboration with WP5.1 on knowledge dissemination will be critical for maximum impact of this task. This activity will likely be only an initial effort in this field that we envisage continuing well beyond the conclusion of CRESCENDO.

Deliverables (brief description and month of delivery) D4.3.1: Report on the best use of CMIP6 scenario output for impacts research and policy guidance (M60) **Milestones** M4.3.1: Framework for sampling CMIP6 scenarios with project ESMs agreed (M24) M4.3.2: ESM simulations sampling relevant CMIP6 scenarios completed and made available to WP5.2 for saving on the ESGF (M45)

Work package number	5.1	**Start Date or Starting Event**				M1-60	
Work package title	Knowledge Dissemination						
Participant number	1	5	14	3	7	20	2	10
Short name of participant	UNIVLEEDS	MOHC	UEA	MPG	DLR	PIK	CNRS-IPSL	SMHI
Person/months per participant	27	12	15	4	4	4	4	12

Objectives This WP will use novel methods of knowledge dissemination targeting a range of groups including; *policy and decision makers, UNEP/UNFCCC and similar organisations, the international Earth system/climate research community, climate impacts and regional climate downscaling communities, adaptation and mitigation researchers and the interested public*. A variety of approaches will be utilised to ensure the needs of each group are addressed. We will also emphasize training in science communication for Early Career Scientists (ECS), aiming to increase the ability of young scientists to engage with non-experts in science communication. Links with other Horizon 2020, FP7 and national projects will be initiated, or existing collaborations built upon, to reduce duplication of effort and maximize project impact.

Description of work

Task 5.1.1 Targeted interaction with policy makers (UNIVLEEDS, UEA, MOHC, CNRS-IPSL, MPI, UNIVLEEDS)

We will develop a set of guidance documents on Earth system modelling and projections targeted to policymakers. Focused policy events building on formats developed by partners in other FP7 and national projects (e.g. HELIX, AVOID, IMPACT2C) will be organized, with two such events planned: one to introduce the ScenarioMIP data; and another on CRESCENDO contributions to narrowing uncertainty in future carbon budgets. These events will take place in Brussels or be aligned with a major event such as COP, so the appropriate audiences are attracted. Where possible events will be coordinated with other EU projects to maximize the utility of knowledge provided and avoid event overload. Similar guidance notes will also be developed for organisations such as UNEP, UNFCC, the European Commission, Future Earth, ICSU and WCRP, focussing on their specific needs. Partners, UEA and MOHC have good connections with these communities which will be further developed in this activity.

Task 5.1.2 Science communication training (UEA, SMHI, UNIVLEEDS, MPI, DLR, CNRS-IPSL)

To improve the future ability and engagement of ECS' in science communication, in collaboration with other H2020/FP7 projects, CRESCENDO will organise a set of training workshops and best practice guidance notes on *Earth system science communication to the public and policymakers*.

Task 5.1.3 Guidance for the impacts and downscaling communities (PIK, MOHC, UNIVLEEDS, SMHI)

This task supports work in WP5.2 to develop appropriate guidance/best practice documents to ensure the climate impacts and regional downscaling communities can access, utilise, and fully benefit from CRESCENDO and other CMIP6 data. A sustained two-way dialogue will be maintained between CRESCENDO and major international projects in climate impacts research and regional climate downscaling.

Task 5.1.4 Improving public knowledge of Earth system models and projections (SMHI, MOHC, UEA, UNIVLEEDS)

A website on how Earth system models work, including how they represent the Earth system and generate future projections, will be designed targeted to a public audience and incorporating appropriate visualisation tools, such as HELIXSCOPE being developed in FP7 HELIX by project partners UEA. The focus will be on attracting the non-scientist/specialist to engage and gain knowledge in a fun and user friendly manner on the complex concepts of Earth system modelling and change.

Task 5.1.5 Interaction between CRESCENDO and CMIP6(DLR, UNIVLEEDS, MOHC, PBL, UNEXE, ETH)

DLR (Veronika Eyring, CMIP panel chair) will be the main contact between CRESCENDO and both the CMIP panel and the WCRP Working Group on Coupled Modelling (WGCM). Scientists from MOHC, UNEXE, PBL and ETH are all members of the ScenarioMIP panel and will provide strong interaction with this group. Such interactions will ensure the project is aligned with, and informed of, CMIP plans, while conversely updating the CMIP, WGCM and ScenarioMIP panels on progress in the project. The project coordinator (UNIVLEEDS) will also be actively engaged in this task.

Deliverables

D5.1.1 Two user and policy events; launching the scenario MIP data, and focused on narrowing uncertainty in the carbon budget (M42 and M54)

D5.1.2 Policymaker oriented information sheets on Earth System modeling, ScenarioMIP data and narrowing uncertainties in the carbon budget (M12, 42 and 54)

D5.1.3 Public web portal on the methodologies and process of building Earth system models and projections (M30).

D5.1.4 Workshop on science communication for young CRESCENDO scientists held in conjunction with a similar HELIX workshop (M30)

D5.1.5 Guidance notes directed to the regional climate downscaling and impact modelling communities on accessing and best practices for CRESCENDO/CMIP6 ESM simulation data (M42)

D5.1.6 Workshop on using CMIP6 projections for climate impacts research (M45)

Work package number	5.2	**Start Date or Starting Event**			Month 1-60			
Work package title	Data dissemination							
Participant number	11	3	20	2	13	10	4	9
Short name of participant	UREAD	MPG	PIK	CNRS-IPSL	MF-CNRM	SMHI	CMCC	METNO
Person/months per participant	5	5	25	9	5	11	5	2

Short name of participant (cont.)	UiB
Person/months per participant (cont.)	3

Objectives

This WP will ensure ESM data is saved on the ESGF. This will be carried out by seven modelling centres that all have prior experience of this from CMIP5 and run, or are closely affiliated with, national ESGF nodes.

The WP will also strengthen collaboration between the ESM community and both the climate impacts and regional climate downscaling communities, ensuring variables required by these communities are delivered from key simulations (e.g. ScenarioMIP). It is often necessary to post process ESM output to “correct” systematic biases for subsequent use in climate-impact models. Many impacts are threshold activated (e.g. tree mortality above a certain temperature), requiring driving climate data corresponds to realistic baseline levels, in terms of mean values and variability. If carefully applied, bias correction can increase the utility of ESM data for use in climate-impact models. Existing trend-preserving bias-correction methods, developed within ISI-MIP, will be improved, with a special focus on the representation of extreme weather events.

Description of work

Task 5.2.1 Archiving ESM data on the ESGF (<u>CNRS-IPSL</u>, UREAD, MPG, CNRM, SMHI, CMCC, METNO, UiB)

ESM modelling groups will ensure key CRESCENDO simulations (e.g. ScenarioMIP, CMIP DECK and runs made for five CMIP6 MIPs to which the project contributes) are saved in a timely manner onto the ESGF. All data will adhere to CMIP6 guidelines. This will be carried out in close collaboration with the FP7 projects; IS-ENES2 and CLIP-C, in which CRESCENDO partners participate. Multi-level data from key simulations will also be saved for use in driving regional climate models and for statistical downscaling.

Task 5.2.2 Communication with impacts-modelling and regional climate downscaling communities (<u>PIK</u>, SMHI)

Contact with the climate-impacts community are already established through ISI-MIP and HELIX and with the regional downscaling community through CORDEX. Data requirements of these communities will be documented and a regular dialogue maintained to ensure both communities are aware of the delivery timescales in CRESCENDO and CMIP6 and to ensure the project is responsive to the needs of each community.

Task 5.2.3 Development and application of bias-correction methods (<u>PIK</u>, SMHI)

The trend-preserving bias-correction method from the ISI-MIP Fast Track will be further developed to better represent extreme weather events. Collaboration between ISI-MIP and CRESCENDO will ensure bias correction methods preserve model simulated trends and variability changes. Improved bias-correction methods will be applied to a selection of CMIP6/CRESCENDO simulations based on suitable sampling of *the dry, wet, hot, cold climate change spectrum*, to facilitate coverage of this phase space in terms of climate change impacts. Bias-corrected data will be made available, in a supported manner, to the ISI-MIP community. Public availability of the bias-correction code will facilitate bias-correction of further CMIP6 runs. Bias-corrected ESM data will be analysed to establish how well extreme weather events are reproduced and compared to uncorrected ESM data. A document describing the appropriate use of bias-corrected ESM data in climate impacts research will be prepared.

Deliverables

D5.2.1 Report of the new bias-correction method, with code made publicly available (M36).
D5.2.2 ESM simulation data saved on the ESGF (*continuous through the project, M60*)
D5.2.3 ESM ScenarioMIP data made available on the ESGF (M48)
D5.2.4 Best practice guide on the use of bias-correction methods and associated ESM data in climate

impacts modelling (M48)
D5.2.5 Bias-corrected ESM ScenarioMIP data made available to the ISI-MIP community (M52).

Milestones
M5.2.1 Requirements of the ISI-MIP and CORDEX communities communicated to CRESCENDO (M3)
M5.2.2 Improved bias correction methods tested and documented using CMIP5 and CMIP DECK runs (M36)

Work package number	6	**Start Date or Starting Event**				Month 1-60		
Work package title	Project management								
Participant number	1	6	18	16	14	5	7	20	3
Short name of participant	UNIVLEEDS	UNEXE	PBL	ETH	UEA	MOHC	DLR	PIK	MPG
Person/months per participant:	55	1	1	1	2	2	1	1	1

Objectives

We note here that the Project Office (project coordinator and project manager) will devote a significant fraction of their project-funded time to external project dissemination. Person months allocated to this task, as well as the work involved, are detailed in WP5.1 in order to ensure regular interaction with the project knowledge dissemination workpackage. WP objectives include:

- Provide management to achieve project objectives on time, to cost and at a high quality by steering functions, ensuring preparation of deliverables, and periodic reporting.
- Ensure the technical, administrative, financial and contractual coordination at project level.
- Ensure effective interaction with the European Commission, consultation with the international advisory board, and represent the project towards external parties.
- Ensure good communication between partners and promote collaborative efforts towards the common goals. Guide RT/WP leaders towards most project-efficient prioritisations to fulfil expectations between partners and keep-up the high ambitions throughout the project period.
- Initiate and facilitate the management related meetings such as General Assemblies, Scientific Steering Committee Meetings etc.
- Ensure active and beneficial collaboration with relevant other EU projects and international bodies.

Description of work

Task 6.1 Management (UNIVLEEDS, UNEXE, UEA, UKMET, DLR, PIK, MPI, PBL, ETH)

This task aims to ensure smooth running of the project, supervising progress and completion of each partner's tasks, in order to achieve the project objectives on time and to cost in the most efficient way. The coordinator supported by the project office, located at ULEEDS, will be in regular contact with the Scientific Steering Committee (SSC) at 3 monthly intervals. Management involves the following main tasks:

- Establishing planning mechanisms for RT/WP level management; time and resources management, reporting tools, development of project templates, maintenance of action and decision-lists;
- 6 monthly internal scientific and financial reporting;
- Establishment of optimal communication between project bodies & partners including provision of document and information sharing platform;
- Supporting RT5 in development and content provision of the public-facing project website;
- Scheduling, organisation, chairing and follow up of project management meetings and supporting RT

leaders in organising their RT specific management meetings in advance of SSC meetings;
- Scheduling, organisation, chairing and follow up of consultations with the International advisory board;
- Supporting the management and development of collaborations outside of the project (with other EU projects, international organisations and bodies such as WGCM, ISI-MIP, CORDEX. JPI-climate and the Copernicus Climate Service etc) in line with RT5.
- Decision making and conflict solving;
- Review of project dissemination materials and scientific publications to ensure quality and adherence to EC guidelines; and
- Ensuring all reports and deliverables are prepared and delivered on time and are of high quality.

Task 6.2 Reporting and interfacing with the European Commission (UNIVLEEDS)
Timely, quality reports on the scientific and financial progress of the project and interfacing with the European Commission will be the responsibility of the project office. The coordinator will be the single contact point for the EC and for strategic issues outside the project. This task will ensure appropriate follow-up of specific obligations deriving from the EC contract, in terms of reporting (financial and science - results), communication and general management procedures. It will inform the EC of project achievements and any deviations from the agreed plans. In case of major difficulties, it will carry out a dialogue with the EC in order to find an appropriate solution. The clear management structure will ensure efficient communication between and among project partners, associated experts and the EC.

Deliverables

D6.1: Management related meetings: Ongoing project management by the Project Office including follow up of project progress, communication with the consortium, project governance, regular internal reporting, and efficient communication of project progress to EC (M60).

D6.2: Data Management Plan (M6)

Milestones
M6.1 Consortium Agreement (CA agreed and signed M1)
M6.2 Internal project communication guidance for partners (M3)

Table 3.1b: List of work packages

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
RT1: Improving process parameterizations in ESMs						
1.1	Improving ESMs: Terrestrial biogeochemical processes	3	MPG	230	1	60
1.2	Improving ESMs: Marine biogeochemical processes	2	CNRS-IPSL	202	1	60
1.3	Improving ESMs: Natural aerosols and trace gases	5	MOHC	197	1	60
RT2: Process-level evaluation of improved parameterizations						
2.1	Evaluating terrestrial processes in ESMs	3	MPG	110	1	60
2.2	Evaluating marine processes in ESMs	13	MF-CNRM	93	1	60
2.3	Evaluating natural aerosols and trace gas processes in ESMs	1	UNIVLEEDS	89	1	60
RT3: Evaluation and analysis of ESM simulations						
3.1	Towards routine benchmarking of ESMs	3	MPG	125	1	60
3.2	Understanding and constraining model projections	6	UNEXE	201	1	60

3.3	Quantification of forcing and feedbacks	11	UREAD	63	18	60
RT4: New scenarios and ESM projections						
4.1	Novel climate scenarios and future projections: the CMIP6 Scenario MIP	23	IIASA	108	1	30
4.2	Assessing the robustness of ESM performance and projection response to model resolution	5	UREAD	73	1	36
4.3	Organising ESM simulations for CMIP6 ScenarioMIP	10	SMHI	90	24	60
RT5: Knowledge and data dissemination						
5.1	Knowledge Dissemination	10	SMHI	79	1	60
5.2	Data dissemination	20	PIK	70	1	60
RT 6: Project Management						
6	Project management	1	UNIVLEEDS	65	1	60
			TOTAL	1795		

Table 3.1c: List of Deliverables

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date
D1.1.1	Report describing improved representation of terrestrial processes in European ESMs	1.1	MPG	R	PU	M60
D1.2.1	Report describing improved marine process in European ESMs	1.2	CNRS-IPSL	R	PU	M60
D1.3.1	Report describing improved representation of natural aerosol and trace gas processes and couplings in European ESMs	1.3	MOHC	R	PU	M60
D2.1.1	Report describing improved representation of terrestrial processes in European ESMs	2.1	MPG	R	PU	M60
D2.2.1	Report describing improved representation of marine processes in European ESMs	2.2	CNRM	R	PU	M60
D2.3.1	Report on process-level evaluation of aerosol and trace gas improvements in European ESMs.	2.3	UNIVLEEDS	R	PU	M60
D3.1.1	Benchmarking of CMIP DECK runs made by project ESMs	3.1	DLR	OTHER	PU	M38
D3.1.2	ESMValTool 2.0 release	3.1	SMHI	OTHER	PU	M60

D3.2.1	Paper on the theoretical basis for emergent constraints	3.2	UHAM	R	PU	M30
D3.2.2	Synthesis Report on new emergent constraints and key aspects of current climate that determine the fidelity of climate projections	3.2	UNEXE	R	PU	M60
D3.2.3	Report on the weighting of CMIP6/CRESCENDO projections	3.2	DLR	R	PU	M60
D3.3.1	Report on the sensitivity of aerosol radiative forcing to improvements and uncertainty in the representation of the pre-industrial aerosol state	3.3	UNIVLEEDS	R	PU	M52
D3.3.2	Report on the contribution of heterogeneous forcing agents to historical climate change	3.3		R	PU	M54
D3.3.3	Report detailing the ERFs for natural and anthropogenic forcing agents in ESMs and the Climate feedback matrix	3.3	UREAD	R	PU	M60
D4.1.1	Report describing the new IAM scenarios as part of the CMIP6 ScenarioMIP data.	4.1	IIASA	R	PU	M30
D4.2.1	Report on the traceability of performance and future projection responses between low and standard resolution ESMs	4.2	UREAD	R	PU	M36
D4.3.1	Report on the best use of scenarioMIP output for impacts research and policy guidance	4.3	SMHI	R	PU	M60
D5.1.1	Two user and policy events; launching the scenario MIP data and focussing on narrowing uncertainty in the carbon budget	5.1	MOHC	DEC	PU	M42, 54
D5.1.2	Policymaker oriented information sheets on Earth System modelling, ScenarioMIP data and narrowing uncertainties in the carbon budget	5.1	UNIVLEEDS	DEC	PU	M12, 42, 54

D5.1.3	Public web portal on the methodologies and process of building Earth system models and projections	5.1	SMHI	DEC	PU	M30
D5.1.4	Workshop on science communication for young scientists held in conjunction with a similar HELIX workshop	5.1	UEA	OTHER	PU	M30
D5.1.5	Guidance notes directed to the regional climate downscaling and impact modelling communities on accessing best practices for CRESCENDO/CMIP6 ESM simulation data.	5.1	PIK	R	PU	M42
D5.1.6	Workshop on using ScenarioMIP simulations for climate impacts research	5.1	PIK	OTHER	PU	M45
D5.2.1	Report of new bias-correction method, with code made publicly available	5.2	PIK	R	PU	M36
D5.2.2	ESM simulation data saved on the ESGF	5.2	CNRS-IPSL	OTHER	PU	M60
D5.2.3	ESM ScenarioMIP data made available on the ESGF	5.2	CNRS-IPSL	OTHER	PU	M48
D5.2.4	Best practice guide on the use of bias-correction methods and associated ESM data in climate impacts modelling	5.2	PIK	R	PU	M48
D5.2.5	Bias-corrected ESM ScenarioMIP data made available to the ISI-MIP community	5.2	PIK	OTHER	PU	M52
D6.1	Management related meetings	6	UNIVLEEDS	R	PU	M60
D6.2	Data management plan	6	UNIVLEEDS	R	PU	M6

Table 3.2a: List of milestones

Milestone number	Milestone name	Related work package(s)	Estimated date	Means of verification
1.1.1	Protocol of model simulations for evaluation tests ready	1.1	M6	Internal report
1.1.2	First set of offline simulations with initial improvements in terrestrial processes delivered to WP2.1.	1.1	M24	Delivery of simulation data

1.1.3	Consolidated representation of land use in ESMs	1.1	M24	Model code updated and running
1.1.4	Key C^4MIP simulations performed	1.1	M30	Data delivery
1.1.5	Key LUMIP simulations performed	1.1	M30	Data delivery
1.1.6	Key LS3MIP simulations performed	1.1	M30	Data delivery
1.1.7	Second set of offline simulations with further improved terrestrial processes delivered to WP2.1	1.1	M52	Delivery of simulation data
1.1.8	Final improved versions of terrestrial modules implemented in project ESM	1.1	M60	Model code updated and running
1.2.1	(Joint OCMIP) milestone on agreed protocol for ocean forced simulations	1.2	M6	Internal report
1.2.2	First set of offline simulations with initial improvements in ocean physics and biogeochemistry provided to WP2.2	1.2	M24	Delivery of simulation data
1.2.3	Key OCCMIP simulations performed	1.2	M36	Delivery of simulation data
1.2.4	Second set of offline simulations with further improvements in ocean physics and biogeochemistry provided to WP2.2	1.2	M52	Delivery of simulation data
1.2.5	Final improved versions of marine modules implemented in project ESMs	1.2	M60	Model code updated and running
1.3.1	Protocol of model simulations for evaluation tests ready	1.3	M6	Internal report
1.3.2	Initial set of atmospheric simulations with improved processes provided to WP2.3	1.3	M24	Delivery of simulation data
1.3.3	Key AerChemMIP simulations performed (M36)	1.3	M36	Delivery of simulation data
1.3.4	Improved coupling between terrestrial emissions and chemistry/aerosol components	1.3	M48	Model code updated and running
1.3.5	Improved coupling between marine emissions and chemistry/aerosol components	1.3	M48	Model code updated and running
1.3.6	Improved SOA schemes and deposition to terrestrial and marine carbon cycles	1.3	M48	Model code updated and running
1.3.7	Second set of atmospheric simulations with improved processes provided to WP2.3	1.3	M52	Delivery of simulation data
2.1.1	Report on data and model output requirements needed for evaluation	2.1	M6	Internal report
2.1.2	Framework for evaluating offline simulations made in WP1.1 available.	2.1	M18	Internal report
2.1.3	Initial set of terrestrial biogeochemistry metrics available to RT3 for ESMValTool	2.1	M20	Metrics code provided to RT3
2.1.4	Process-evaluation of the initial model simulations and feedback to RT1	2.1	M30	Internal transfer of information/report
2.1.5	Complete set of terrestrial	2.1	M52	Metrics code provided

	biogeochemical metrics delivered to the ESMValTool repository			to RT3
2.1.6	Process-evaluation of improved model simulations and feedback to RT1	2.1	M54	Internal transfer of information/report
2.2.1	Report on data and model output requirements needed for evaluation	2.2	M6	Internal report
2.2.2	Framework for evaluating offline simulations made in WP1.2 available.	2.2	M18	Internal report
2.2.3	Initial set of marine biogeochemistry metrics available for ESMValTool	2.2	M20	Metrics code provided to RT3
2.2.4	Process-evaluation of the initial model simulations and feedback to RT1	2.2	M30	Internal transfer of information/report
2.2.5	Complete set of marine biogeochemical metrics delivered to the ESMValTool repository	2.2	M52	Metrics code provided to RT3
2.2.6	Process-evaluation of improved model simulations and feedback to RT1	2.2	M54	Internal transfer of information/report
2.3.1	Report on data and model output requirements needed for evaluation	2.2	M6	Internal report
2.3.2	Framework for evaluating offline simulations made in WP1.3 available.	2.1	M18	Internal report
2.3.3	Initial set of aerosol metrics available for ESMValTool.	2.1	M20	Metrics code provided to RT3
2.3.4	Process-evaluation of the initial model simulations and feedback to RT1	2.3	M30	Internal transfer of information/report
2.3.5	Complete set of aerosol and trace gas metrics available to ESMValTool	2.3	M52	Metrics code provided to RT3
2.3.6	Process-evaluation of improved model simulations and feedback to RT1	2.3	M54	Internal transfer of information/report
3.1.1	ESMValTool prototype implemented on key ESGF nodes	3.1	M18	Software tested and running
3.1.2	ESMValTool with new diagnostics	3.1	M24	Software tested
3.1.3	ESMValTool (internal) release for CMIP DECK evaluation	3.1	M32	Software released internally
3.1.4	Consolidated software release, including all project diagnostics, routine testing for internal verification	3.1	M56	Software released internally
3.2.1	Initial analysis of CMIP5 models for previously identified Emergent Constraints	3.2	M12	Internal report
3.2.2	Initial theoretical guidance on the links between the current climate variability and ES sensitivity	3.2	M18	Internal report
3.2.3	First workshop: Emergent Constraints – in theory and in CMIP5 models	3.2	M24	Workshop held
3.2.4	Exploration of new Emergent Constraints on physical, biophysical, carbon cycle and aerosol feedbacks in CMIP5.	3.2	M36	Internal report
3.2.5	Exploration of Emergent Constraints in the latest CRESCENDO/CMIP6 simulations and comparison to CMIP5	3.2	M54	Internal report
3.2.6	Second workshop: Emergent	3.2	M54	Workshop held

	Constraints – robustness across model generations			
3.3.1	Climate feedback matrix framework available	3.3	M30	Internal distribution of data/report
3.3.2	ERF simulations completed	3.3	M40	Data made available
3.3.3	Transient simulations completed	3.3	M45	Data made available
4.1.1	Report assessing the level of uncertainty space sampled by the scenarioMIP tier 1 scenarios compared to the full range of CMIP6 scenario forcing uncertainty.	4.1	M20	Internal report
4.1.2	Final delivery of a set of new scenarios as part of the CMIP6 ScenarioMIP	4.1	M24	Data delivery
4.1.3	Evaluation report on preliminary ESM sampling of IAM scenarios.	4.1	M24	Internal report
4.2.1	Low resolution versions of ESMs run for a subset of CMIP DECK simulations	4.1	M30	Data made available
4.2.2	Recommendations on the use of low and standard resolution ESMs for SceanrioMIP.	4.1	M32	Internal report
4.3.1	Framework for sampling ScenarioMIP data with project ESMs agreed	4.3	M24	Internal transfer of information/report
4.3.2	ESM ScenarioMIP simulations completed and made available to WP5.2 for saving on the ESGF	4.3	M45	Data delivery
5.2.1	Requirements of the ISI-MIP and CORDEX communities communicated to CRESCENDO modelling groups	4.3	M3	Internal report
5.2.2	Improved bias correction methods tested and documented.	4.3	M36	Internal report
6.1	Consortium agreement (CA)	6	M1	CA agreed and signed
6.2	Internal project communication guidance for partners	6	M3	Document produced and distributed

Research Theme (RT)	WP number	Work Package (WP) Title	Year 1												Year 2												Year 3											
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
RT1	1.1	Improving ESM's:Terrestrial biogeochemical processes						M																		M						M						
	1.2	Improving ESMs: Marine biogeochemical processes						M																		M												
	1.3	Improving ESMs: Natural aerosols and trace gases						M																		M												M
RT2	2.1	Evaluating terrestrial processes in ESMs						M												M		M										M						
	2.2	Evaluating marine processes in ESMs						M												M		M										M						
	2.3	Evaluating natural aerosols and trace gas processes in ESMs																														M						
RT3	3.1	Towards routine benchmarking of ESMs																		M						M								M				
	3.2	Understanding and constraining model projections												M						M						M						D						M
	3.3	Quantification of forcing and feedbacks																														M						M
RT4	4.1	Novel climate scenarios and future projections: the CMIP6 Scenario MIP																				M				M						M D		M				
	4.2	Assessing the robustness of ESM performance and projection response to model resolution																																				D
	4.3	Organising ESM simulations for ScenarioMIP																								M												M
RT5	5.1	Knowledge dissemination						M																								D						
	5.2	Data dissemination			M																																	M D
RT6	6	Project Management	M		M			D						GA												GA												GA

Research Theme (RT)	WP number	Work Package (WP) Title	Year 4												Year 5											
			37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
RT1	1.1	Improving ESM's:Terrestrial biogeochemical processes																M								M D
	1.2	Improving ESMs: Marine biogeochemical processes																M								M D
	1.3	Improving ESMs: Natural aerosols and trace gases												M				M								D
RT2	2.1	Evaluating terrestrial processes in ESMs																M		M						D
	2.2	Evaluating marine processes in ESMs																M		M						D
	2.3	Evaluating natural aerosols and trace gas processes in ESMs																M D		M						D
RT3	3.1	Towards routine benchmarking of ESMs		D																		M				D
	3.2	Understanding and constraining model projections																		M						D
	3.3	Quantification of forcing and feedbacks									M			D						D						D
RT4	4.1	Novel climate scenarios and future projections: the CMIP6 Scenario MIP																								
	4.2	Assessing the robustness of ESM performance and projection response to model resolution																								
	4.3	Organising ESM simulations for ScenarioMIP									M															D
RT5	5.1	Knowledge dissemination						D			D									D						
	5.2	Data dissemination												D				D								D
RT6	6	Project Management												GA												D

Figure 3: Gantt chart showing the main project timelines, deliverables and milestones.

3.2 Management structure and procedures

CRESCENDO is an important project for all consortium members. The partners consider project management a key component of achieving the project objectives in an efficient manner. Project management is therefore adequately resourced with a dedicated workpackage (WP6) responsible for providing interim and final results of the project to the European Commission. With a total budget request from the European Commission of ~14.3 million euros, project management constitutes around 4% of the total budget of the project. RT5 will lead on dissemination of project results and knowledge to a range of stakeholder groups. Both the project coordinator and project manager will also play a significant role in external knowledge dissemination. In the context of budgeted time, we envisage $^1/_3$ (~4 months per year) of a full time project manager will be devoted to dissemination, with the project coordinator devoting a similar amount of time. For ease of presentation, this part of the project coordinator and manager time are budgeted directly into RT6, with the remaining time budgeted into WP6 and dedicated to project management, internal project communication and coordination and reporting to the European Commission. The project office and RT5 will have regular interactions so that a single dissemination approach is followed. The project is coordinated by Professor Colin Jones, University of Leeds and Head of the UK Earth System Modelling project.

The management structure of CRESCENDO is designed to allow fast flow of information between the partners, project administration, the European Commission and the wider outside world. A central role will be played by the project administration at the University of Leeds, both in the School of Earth and Environmental Science and the central European Team who will monitor project finances and reporting to ensure all reports and claims are correct and submitted in a timely manner. All practical administration will be handled by experienced administrators at the University. The project will hire a full time project manager who will be responsible for day to day management of the project. The project manager will be the main link between the University of Leeds administration and the project coordinator and the wider project consortium. Scientific management of the project will be integrated within a hierarchical but flexible decision-making structure involving the coordinator, the project office and a Scientific Steering Committee, with the Governing Board acting as the overall decision making body of the project. Additional advisory groups will include an International Advisory Board and Data Protocol Panel (DPP). Principle methods of communication are the internet (e-mail and document sharing), regular tele/videoconferences and project workshops, including general assemblies and task-specific workshops. These are discussed in more detail below. Figure 4 illustrates the general management structure for CRESCENDO.

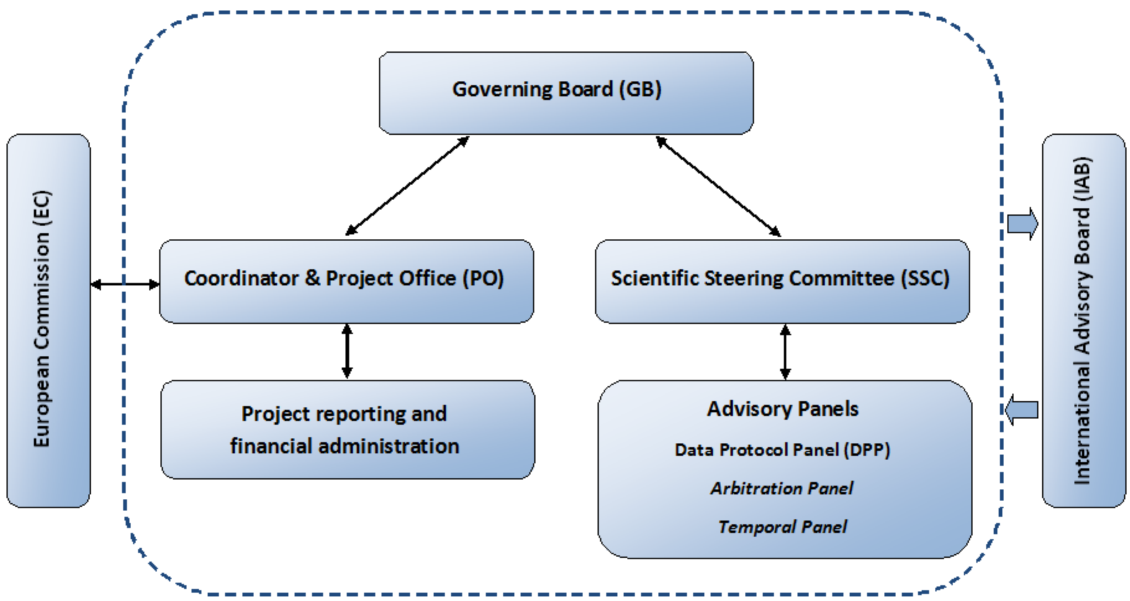

Figure 4: Project management structure of CRESCENDO

3.2.1 Decision making and executive bodies

The Governing Board (GB)

The Governing Board (GB) is the overall decisive body of the consortium and will include one representative from each partner institute. The GB will be chaired by the project coordinator. It is this board which validates the major decisions concerning the project. Any partner may submit for arbitration by the Governing Board any decision by the SSC or project office it deems to be contrary to its interests; the Governing Board is also the decision-making body for any issue concerning the proper operation of the Consortium and will resolve any project disputes arising between partners. In principle, approval by the Governing Board shall be by mail vote with a simple majority required. For a decision to be binding, at least two-thirds of the GB must have cast a vote or had the opportunity to do so. If no majority can be agreed then the chairman will decide the vote. Formal meetings of the Governing Board will be held only during the annual project general assemblies. The matters to be acted upon by the Board 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 (if >10% of EC contribution);
- Any alterations of 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.

The decision and problem resolving process will be defined in detail in a Consortium Agreement, which will be signed by all beneficiaries prior to initiation of the project.

Scientific Steering Committee (SSC)

The main role of the Scientific Steering Committee (SSC) is to lead and follow up on science research carried out in the project. Major decisions or recommendations made by the SSC which change either the scientific or financial direction of the project must be agreed upon by the GB. The SSC responsibilities include:

- Make progress reports on the advancement of the project;
- Provide project deliverables to the Commission;
- Propose any necessary or beneficial changes of the Project budget/membership to the GB;
- Propose and implement the competitive selection procedure for new contractors;
- Make proposals to the Governing Board for changes in consortium membership;
- Lead the proper conduct of the project, and to maximise project output and impact.

The SSC is composed of the Research Theme (RT) leaders and the Coordinator, who chairs the SSC. Two RT leaders have been appointed for each of the project RTs and one WP leader for each of the WPs within a given RT. WP leaders are responsible for ensuring the implementation of the WP is consistent with the overall workplan and that deliverables and milestones under their WP are realized on time and are of high quality. Formal deliverables will be passed from the WP leads to their respective RT leaders who, along with the project coordinator, will act as an internal review process for deliverables prior to submission to the European Commission. At the RT level, the RT leaders assume responsibility for collection and delivery of all due project deliverables. The SSC will meet in person at least once per year coincident with the General Assembly, as well as having 3 tele/video conferences per year. Each RT lead group, consisting of the 2 RT leads and all WP leads of that RT will have quarterly tele/video conference, at least 2 weeks in advance of a scheduled SSC meeting. Such a hierarchical management approach will help to highlight any problems early and maximize efficiency in solving these problems. The following have been selected as RT and WP leads:

RT	RT Leader (RTL)	WP	WP Leader (WPL)
1	Pierre Friedlingstein (UNEXE) Parv Suntharalingam (UEA)	1.1	Victor Brovkin (MPI)
		1.2	Laurent Bopp (CNRS-IPSL)
		1.3	Fiona O'Connor (MOHC)
2	Tatiana Illyiana (MPI) Chris Jones (MOHC)	2.1	Soenke Zaehle (MPI)
		2.2	Roland Séférian (CNRM)
		2.3	Ken Carslaw (UNIVLEEDS)
3	Veronika Eyring (DLR) Reto Knutti (ETH)	3.1	Alex Loew (MPI)
		3.2	Peter Cox (UNEXE)
		3.3	Bill Collins (UREAD)
4	Jason Lowe (MOHC) Detlef van Vuuren (PBL)	4.1	Keywan Riahi (IIASA)
		4.2	Till Kuhlbrodt (UREAD)
		4.3	Ralf Doescher (SMHI)
5	Katja Frieler (PIK) Asher Minns (UEA)	5.1	Eleanor O'Rourke (SMHI)
		5.2	Sebastien Denvil (CNRS-IPSL)
6	Colin Jones (UNIVLEEDS)	6	Colin Jones (UNIVLEEDS)

Table 3: CRESCENDO RT and WP leaders (partner institute)

WP leaders will ensure good communication within in a given WP while RT leaders will ensure cross-WP and cross-RT collaboration and communication. The RT leaders of themes 1 to 4 will also be responsible for ensuring important knowledge and information from their RTs is communicated to RT5 for dissemination in a timely manner. This will occur in close collaboration with the project office.

Project Coordinator and Project Office

The project will be coordinated in all financial, administrative and managerial aspects by the University of Leeds as stated by the European Commission contracting rules. Prof. Colin Jones will act as the project coordinator. He has a long track record of project coordination, leading the EU FP7 project EMBRACE, was joint coordinator of the WCRP project CORDEX and member of the WCRP Working Group on Coupled Modelling (WGCM). He now heads the UK Earth System Modelling project and was formerly head of the Rossby Centre at the Swedish Meteorological and Hydrological Institute and before this Director of the Canadian Regional Climate Modelling and Diagnostics Network. He has been an active partner in numerous earlier EU projects. The Coordinator will be responsible for the management of CRESCENDO and liaison with the European Commission on behalf of the consortium. He will also be the principle contact to the financial administration at the University of Leeds. When necessary he can convene full SSC meetings. The Coordinator, assisted in the day-to-day work by the members of the project office, in particular the project manager, has the responsibility of overall co-ordination and management of 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 SSC;
- Day to day co-ordination of the project; monitoring project planning and progress;
- Communication within the project, to users, and to 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

Implementation of the plans under knowledge and innovation-related activities, intellectual property issues and Gender Action Plan will be under the responsibility of the coordinator.

The coordinator heads the CRESCENDO Project Office, which will be established through the University of Leeds. The project office (PO) will comprise the coordinator and a project manager (PM), with assistance from experienced project administrators at the University within the Faculty of Environment and the central European Office. The PM assists the Coordinator in the day to day monitoring of the Project (follow-up of planning schedule, issue reminders for task initiation or completion, all other issues listed above), identifies and anticipates problems and proposes actions to remedy them. The PM maintains the internal project communication instruments: a document and information sharing platform, mailing lists and regular tele/video conferences. The PM will assist the Coordinator in the preparation of the periodic reporting including finances and in the financial actions between the Commission and the project partners. The PO will be responsible for organizing the consortium general assemblies and any physical meetings of the project management bodies. Both the project coordinator and manager will play an active role in project dissemination, through a tight collaboration with RT5.

Project financial administration

The financial administration of CRESCENDO will be carried out by experienced staff at the University of Leeds. Its responsibilities include:

- receiving the entire financial contribution from the Commission. With advice from the Project Coordinator it will manage this contribution by allocating it to the Contractors pursuant to the "Work Plan" and the decisions taken by the appropriate bodies.
- preparing annual accounts, if requested by the Commission or by the Contractors, to inform them of the distribution of funds among the Contractors;
- the overall financial management of the coordination,
- Coordination of the financial annual reporting in line with the financial rules of FP7
- Clarifying any problem pertaining to the budgets raised by partners or the Commission

Advisory panels

Data protocol panel (DPP)
As outlined earlier the project will have a DPP responsible for data management in the project. The DPP will have close contact with similar bodies, particularly IS-ENES2 and the WGCM Infrastructure Panel. The DPP will be answerable to the SSC, and will produce a data management plan (DMP) in line with the 'Guidelines of Data Management in Horizon 2020' and be responsible for monitoring the project's adherence to this.

Arbitration and *temporal panels* will be created as and when required.

International advisory board (IAB)

CRESCENDO will establish an International Advisory Board of distinguished scientists to ensure external evaluation of the project and links to other activities outside Europe. The functions of the IAB will be:

- Advising on the project scientific approach and orientation by liaison with the SSC and coordinator;
- Advising and assist on the project knowledge dissemination;
- Providing a link to related activities both inside and outside Europe;
- Providing an international perspective on developments in the field of Earth system modelling.
- Making recommendations for new actions and activities in this area

Regular consultation of the IAB will aid in CRESCENDO supporting the overall aims of the EU and the international ESM community, as manifested through bodies such as WCRP and Future Earth. The IAB will meet at least once per year, generally at the project General Assembly and receive an executive report, in advance of each meeting detailing the status of the project together. The following members are confirmed:

- *Dr Clare Goodess: Senior Research Scientist at the Climatic Research Unit, UEA and co-chair of the WCRP Working Group on Regional Climate (WGRC)*
- *Dr William Large: Director of the Division of Climate and Global Dynamics, National Center for Atmospheric Research, Colorado, USA*
- *Professor James Randerson: Professor of Earth System Science, University of California, Irvine, USA*
- *Professor Sir Robert Watson: Director of Strategic Development, Tyndall Centre, UK, Vice-Chair of IPBES (Intergovernmental Panel on Biodiversity and Ecosystem Services) and Chair of the (interim) Future Earth Engagement Committee.*
- *Ms. Denise Young: Head of communication, International Council for Science (ICSU).*

3.2.2 International Collaboration and coordination

CRESCENDO will maintain strong links with international activities in Earth System Modelling, through individual partner contacts and participation on a range of panels, including WCRP and Future Earth. We have established collaboration with a number of non-European institutes who will work with CRESCENDO on an unfunded status. In the proposal we have requested funds to support one scientist from each of the collaborating institutes to attend the five CRESCENDO annual project meetings. This will facilitate direct contact and exchange between CRESCENDO scientists and lead scientists at the collaborating institutes, helping to increase knowledge exchange and, particularly, encouraging our collaborators to perform simulations following CRESCENDO protocols and timelines, increasing the ensemble of simulations available for analysis in the project. Such collaboration will ensure CRESCENDO is at the heart of international Earth system modelling over the coming years. Participation of non-European institutes brings an extra level of science input to the project while also increasing the potential for shared science developments, coordinated model simulations and the sharing of evaluation methodologies and observations. Given the truly global nature of climate and Earth system change, international collaboration is, and has always been, at the heart of CMIP activities and IPCC Assessment cycles. We view active international collaboration as critical for driving forwards our (combined) ability to provide reliable information of future Earth system change to all global leaders and citizens. It is from this perspective that we view international collaboration as a major benefit to CRESCENDO. The collaborating institutes and names of contact scientist are:

- The Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University (*Dr John Dunne*, (Head of) and *Dr Jasmin John* (member of) GFDL Biochemistry, Ecosystems and Climate Group)
- The National Center for Atmospheric Research (NCAR) (*Dr. Jean-François Lamarque*, Community Earth System Model (CESM) Chief Scientist and *Dr William Large*, Director of Climate and Global Dynamics).
- The Centre for Australian Weather and Climate Research (CAWCR, *Dr Rachel Law*) Earth System Modeling team
- The New Zealand National Institute of Water and Atmospheric research (NIWA) Earth system modeling team (*Dr Olaf Morgenstern*)
- The South African Council for Scientific and Commonwealth Research (CSIR) Earth system modeling program (*Dr Francois Engelbrecht and Dr Pedro Monteiro*)
- The Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory, USA (*Dr Peter Gleckler*).
- NASA Jet Propulsion Laboratory, California Institute of Technology (*Professor Duane Waliser and Dr Robert Ferraro*)
- The School of Earth Sciences, University of Melbourne (*A/Professor M. Meinhausen*).

The first three institutes (GFDL, NCAR and CAWCR) are major Earth System Modelling centres already contributing to the CMIP exercise. The New Zealand “Deep South” consortium is a new Earth system science initiative with a focus on the role of the Southern Ocean and Antarctica. Similarly, CSIR is a new South African initiative to develop an Earth system model, with primary focus on Africa and the Southern Ocean. Collaboration with these two groups will help development of their ESM capabilities, while also increasing science expertise and observations for three key regions of Earth system change (Southern Ocean, Antarctica and Africa). PCMDI play a key role in the WCRP/WGNE climate model metrics panel and already collaborate with CRESCENDO groups on ESM evaluation. PCMDI is also a key player in the ESGF. NASA-JPL lead the Obs4MIP activity and is a key group working at the interface between satellite observations and ESM evaluation. Finally, the University of Melbourne group is a key IAM team participating in development of the socio-economic scenarios supporting ScenarioMIP. Collaboration with all groups will primarily be around shared design and execution of experiments, sharing data and its analysis, the development of analysis tools and joint workshops for sharing knowledge and science progress.

In section 6 of the proposal a letter of intent to collaborate with CRESCENDO is provided from each of the collaborating institutes. Also included in section 6 are two letters of support for CRESCENDO from, respectively, the Director of the WCRP Joint Planning Staff and the co-chairs of the WCRP Working Group on Regional Climate and chair of the CORDEX Science Advisory Team.

3.2.3 Other management issues

Consortium Agreement

A Consortium Agreement (CA) will be signed before the project commences. It will be based on the DESCA model. The CA includes in particular details about:

- The organisation of the consortium, as described above.
- The financial distribution: the consortium agreed on distributing the Community Financial Contributionon the basis of each participant's effort and activity type.
- Procedures for changes in the consortium composition.
- IPR and exploitation: definition of the background brought by all participants and related access
- rights, rules for joint ownership, access rights to project results for participants and 3rd parties
- Dissemination: rules for managing confidentiality and approving public presentations and publications.

Management of knowledge

The consortium agreement will identify pre-existing knowledge and the provisions for intellectual property safeguards. CRESCENDO will take due account of the recommendations of the CMIP6 protocol on data archiving. The project, through collaboration with other EU projects, CMIP6 and WGCM panels will ensure data and knowledge produced in the project is made fully available to all interested scientists. The appropriate unit at the University of Leeds will be involved in the drafting and negotiation of the Consortium Agreements with the Commission and the partners. They will also assist in the follow-up of the implementation and compliance with the terms of the agreement.

Exploitation of project knowledge to support policy and public decision making

Through RT5 CRESCENDO will have a major focus on dissemination of knowledge and data from the project to support the generation of actionable climate change information for Europe, as well as the provision of accurate, high-quality information on future Earth system change (risks and opportunities) to support European policy and decision making. The RT5 leads, along with the project coordinator and project manager will meet regularly to review dissemination activities with an aim to ensure a regular flow of knowledge out of and into the project from key stakeholder groups, such as European, national and regional policy makers. Public engagement will primarily be in the form of targeted online/social media visualizations as well as communication events at suitable science fairs and conferences across Europe. Further detail on the dissemination plans for CRESCENDO can be found in the work package description for WP5.2.

Project meetings

The kick-off meeting marks the effective launch of the project and starts the project work plan. Unresolved issues will be identified and discussed; science and co-operation between RTs and WPS initiated. The coordinator and RT/WP leaders will outline the project aims and what is expected of each group. Other project meetings (e.g. General Assemblies) will be held on an annual basis and timed to assist with the preparation of the interim and final reports from the project They will be complemented and supported by SSC, GB and IAB meetings to be held in the same time frame. Additional SSC meetings, by tele/video conference will take place on a 3-4 monthly basis to ensure progress. RT specific tele/video conferences will be scheduled to occur 2-3 weeks in advance of each SSC meeting. Topical working meetings will be organised by the RT/WP leaders as required in lines with the needs of their specific tasks.

Internal Communication

The project communication strategy aims to keep all the partners fully informed about the status of the different activities in all RTs and WPs. The goal is maximum transparency for all involved parties and hence increased synergy. All reports produced (meeting and project reports, publications etc) will be communicated to the project office and channelled to other partners when appropriate. The project office will make available to partners relevant information obtained from sources outside the project (other projects, international programmes, the European Commission, WCRP or from various other agencies). All documents will be indexed and available to partners on a document and information sharing platform utilising user-friendly open source software if possible. The project office will maintain regular contact with the SSC in line with deliverable and milestone deadlines. Further the project office will provide assistance to RT and WP leads to ensure they can communicate effectively within their relevant RT or WP.

3.2.4 Project Risks and mitigation options

Critical risks for the project are outlined in Table 3.2b with some discussion of possible mitigation options.

Description of risk	**WPs involved**	**Likelihood**	**Impact**	**Proposed risk-mitigation measures**
Poor management leads to deliverables not being achieved on time or at required quality.	WP6	Low	Medium	RT and WP leads have been selected due not only to their expertise but also experience in projects of a similar size ensuring they have the appropriate skills to achieve project goals. The project office will ensure regular communication with RT/WP leads allowing for early warning of any problems that may arise. The project office will provide support, materials, software and guidance to RT/WP leads at all points to help them in their role.
Long term absence of key partners due to illness, accident or parental leave.	All	Low	Medium	Partners will be asked to ensure they inform the project office and relevant RT/WP leads in such an event as soon as possible to allow for contingency planning. As a final option responsibilities may be transferred to another relevant partner to ensure delivery in line with EC regulations.
Delays in recruitment of project personnel	All	Medium	Low to medium	Recruitment of high quality personnel can be problematic; however, partners can utilise the wide network offered by the consortium to advertise positions, supported by the project office. We will instigate the planning of personnel requirements at the project initiation.
Delays in the delivery of simulation data from key CRESCENDO experiments.	RT3, RT4, RT5	Low to medium	Low to medium	CRESCENDO modelling groups contributed simulations to CMIP5, and in many cases to CMIP3. They have extensive experience in the long chain from preparing model experiments, through execution, evaluation and data delivery. Given the basic experiment protocols, for CMIP6 are based on CMIP5, we believe our partners will be able to deliver simulations in a timely manner. For most key simulations there is a relatively wide delivery window (~6 months) to allow for unforeseen problems. As 7 ESMs participate in the project, delays in data delivery from 1 or 2 models, does not need to stop dependent science activities using a reduced ensemble and as new model data becomes available these can be integrated into the analysis.
Improved parameterizations from RT1 perform well in single component model evaluation in RT2, but perform poorly when coupled into full ESMs (likely due to compensating errors from another	RT1, RT2, RT3	Medium	Medium	Such problems are common to ESM development. If this arises RT2 and RT3 will endeavour to understand and isolate what parts of the ESM are causing the problem (assuming the new parameterization has been fully evaluated in RT2) and work with RT1 to try and alleviate the problem. If this is not possible then a last resort is to simplify/adjust the improved parameterization to avoid triggering of compensatory biases, while documenting what modifications have been made. A longer term effort will then be required to utilise the improved parameterization in the full ESM. This will likely require further development of those processes known to be the underlying cause of

component of the ESM).				the coupled ESM biases when interacting with the new scheme. This may imply process improvements made in CRESCENDO, shown to be improvements at the process level, do not enter the coupled ESM until after the conclusion of the project.
Low resolution ESMs do not have an acceptable level of performance relative to their CMIP6 (higher resolution) parent models.	RT4	Low to medium	Medium	The low resolution models targeted for ScenarioMIP have resolutions close to standard CMIP5 models. While these are newer models, there is experience of performance at these resolutions so we are confident an acceptable performance can be achieved. We do expect improved performance from the higher resolution CMIP6 models with respect to higher time and smaller space scale variability. On larger space scales performance is likely to be more similar across the 2 versions. Unacceptable differences may arise. If this occurs we will document the reasons for this lack of traceability and only apply the CMIP6 standard resolution models to a reduced number of ScenarioMIP data and, with the wider community, investigate other possible routes to expand the resulting ensemble size.

3.2 Consortium as a whole

Consortium as a whole

CRESCENDO consists of 24 partners from 10 European countries, bringing together 7 European Earth system models and 3 Integrated Assessment models, as well as expert groups in ESM process parameterization, ESM evaluation methods, emergent constraints, science communication, climate impacts modelling, regional climate downscaling and experts on the Earth System Grid Federation (ESGF). The consortium includes **all** European ESMs currently participating in CMIP, maximizing coordination of European contributions to CMIP6 and the sharing of knowledge and data across Europe. The consortium is a balanced mix of leading European process-parameterization developers in our 3 target areas; terrestrial and marine biogeochemistry and natural aerosols and trace gas chemistry. These scientists work closely with physical model development scientists at each of the modelling centres, hence a strong link is ensured between physical and Earth system model development. The core development team of the ESMValTool (DLR, SMHI and MPG) are all members of the consortium and will lead on making the ESMValTool scientifically complete and technically user-friendly. The consortium has a balanced mix of 9 leading Universities, 7 National Meteorological-Hydrological Institutes and 8 national research centres. Inclusion of 9 universities ensures an appropriate involvement and training of PhD students and postdoctoral level young scientists which we view as an important aspect of the project. Inclusion of senior scientists from all the European ESM development teams ensures that developments in the project will pull through to improving European models used for generating future climate and Earth system projections, while representation of key climate impacts and downscaling groups further increases the likelihood simulations made in CRESCENDO will form the basis of future climate impact assessments for Europe and elsewhere. The ESM centres in the consortium are all experienced in executing major international coordinated simulations (such as for CMIP5 and earlier CMIP exercises) and delivering data in a structured manner onto the ESGF. Furthermore many of the partners are already working together successfully in current FP7 projects such as; EMBRACE, HELIX, IS-ENES2, PAGE-21 and CLIP-C and have a history of working together in past projects, such as FP7 COMBINE, IS-ENES and FP6 ENSEMBLES.

The consortium includes a number of experts on the new discipline of emergent constraints, both with respect to the underlying theory (UHAM) and frontier use of this discipline in constraining Earth system projections (UNEXE, ETH, DLR). The consortium also includes a number of groups (MOHC, UEA, PIK, SMHI and CNRS-IPSL) with extensive experience in science communication directed towards key groups such as; policy/decision makers, the interested public, and complementary research disciplines. To increase the impact of both science and knowledge produced in the project we have ensured the consortium is well linked to, and indeed a n umber of partners are actively involved in, important complementary ongoing international and European projects (e.g. CORDEX, ISI-MIP, FP7 HELIX, is-ENES2, CLIPC, JPI-Climate). As detailed in section 2.1 under: *Collaboration through international bodies and with key partners*, the consortium includes numerous members of WCRP, IGBP, GEWEX and Future Earth panels, including the CMIP panel chair. It also includes leaders of the ISI-MIP climate impacts program and the host institute for the International CORDEX office. Furthermore, a number of the CMIP Model Intercomparison Projects (MIPs) that CRESCENDO is structured to feed into are chaired by consortium members. This type of representation will ensure CRESCENDO science is well represented at international levels and being informed of international plans in Earth system modeling.

As detailed in section 3.2.2 we have established collaboration with a number of major non-European groups involved in ESM development and evaluation, as well as IAM scenario generation. This international dimension increases the potential for CRESCENDO simulations and developed tools and methodologies to become truly international, with input and uptake beyond Europe. Finally, our International Advisory Board (IAB) is deliberately trans-disciplinary covering areas such as; *Earth system model development, observational evaluation of ESM processes, science-policy advice, science communication, and climate impacts and adaptation.* This will ensure CRESCENDO is outward looking in terms of collaboration across all areas of Earth system science and maintains a sustained and high-quality activity in communication/dissemination with both policy and public arenas.

We believe the CRESCENDO 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 productive and high-quality dialogue with both policymakers and the public. Many consortium members are regularly engaged in advising policy on a national level, with a number being lead or contributing authors to the recent IPCC AR5. Furthermore, the consortium will ensure CRESCENDO science influences Earth system science well beyond the conclusion of the project; through the training of Early Career Scientists, the provision of state of the art Earth system projections and through the project delivering the next generation of European Earth System models and evaluation and analysis tools.

3.3 Resources to be committed

Table 3.4a: Summary of staff effort: Person months per partner and work package (WP)

WP	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	6	Total PM
1:UNIV LEEDS	0	0	20	0	0	24	0	21	7	0	6	0	27	0	55	**160**
2:CNRS-IPSL	32	37	32	12	12	10	0	10	9	0	3	5	4	9	0	**175**
3:MPG	42	32	0	22	16	0	14	10	2	0	3	5	4	5	1	**156**
4:CMCC	25	34	0	9	16	0	0	0	0	0	3	5	0	5	0	**97**
5:MOHC	24	0	32	19	0	18	0	12	2	5	6	5	12	0	2	**137**
6:UNEXE	27	0	8	7	0	0	8	36	0	3	0	3	0	0	1	**93**
7:DLR	0	0	0	0	0	0	32	29	8	3	0	3	4	0	1	**80**
8:KNMI	0	0	32	0	0	10	0	0	0	9	0	3	0	0	0	**54**
9:METNO	5	0	32	0	0	10	0	0	9	0	10	0	0	2	0	**68**
10:SMHI	0	12	0	0	3	0	22	0	0	0	12	5	12	11	0	**77**
11:UREAD	0	0	0	0	0	0	19	0	24	0	19	5	0	5	0	**72**

12:ENEA	15	0	0	6	0	0	12	0	0	0	0	0	0	0	0	**33**
13:MF-CNRM	12	21	24	0	10	13	0	0	2	0	3	5	0	5	0	**95**
14:UEA	0	19	0	0	11	0	0	11	0	0	0	0	15	0	2	**58**
15:UHAM	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	**30**
16:ETH	0	0	0	9	0	0	15	36	0	6	0	5	0	0	1	**72**
17:UiB	11	24	0	0	16	0	0	5	0	0	0	5	0	3	0	**64**
18:PBL	0	0	0	0	0	0	0	0	0	30	0	11	0	0	1	**43**
19:ULUND	15	0	8	8	0	4	0	0	0	0	0	0	0	0	0	**35**
20:PIK	0	0	0	0	0	0	0	0	0	22	0	8	4	25	1	**60**
21:NOC	0	22	0	0	10	0	3	0	0	0	8	0	0	0	0	**43**
22:CNR	12	0	9	6	0	0	0	0	2	0	0	5	0	0	0	**34**
23:IIASA	0	0	0	0	0	0	0	0	0	30	0	12	0	0	0	**42**
24:FMI	10	0	0	8	0	0	0	0	0	0	0	0	0	0	0	**18**
Total	**230**	**201**	**197**	**110**	**94**	**89**	**125**	**200**	**61**	**108**	**73**	**90**	**82**	**70**	**65**	**1795**

A number of partners will devote significant in-kind personnel effort to activities in the project. Furthermore, all the project modeling centres contribute a significant amount of in-kind resources to the project in the form of; (i) High Performance computing (HPC) for making CRESCENDO/CMIP6 simulations, (ii) Data storage facilities, linked to the ESGF, for saving model output, (iii) technical support staff for HPC maintenance and efficient running of ESM codes and (iv) parallel development of other aspects of the project ESMs, in particular physical process parameterizations and dynamical cores, that are necessary to realize suitable performance of fully coupled, project improved ESMs. The magnitude of this in-kind contribution is difficult to quantify but is likely equivalent to the funds requested by CRESCENDO from the European Commission. Hence CRESCENDO will lever an enormous amount of in-kind national/institutional effort to realize its project goals.

Table 3.4b: 'Other direct cost' items :

Not applicable to CRESCENDO partners

Please complete the table below for all participants that would like to declare costs of large research infrastructure under Article 6.2 of the General Model Agreement[1], irrespective of the percentage of personnel costs.

Not applicable to CRESCENDO partners

[1] Large research infrastructure means research infrastructure of a total value of at least EUR 20 million, for a beneficiary. More information and further guidance on the direct costing for the large research infrastructure is available in the H2020 Online Manual on the Participant Portal.

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