

## **A: Case for Support: The UK Earth system modelling project: UKESM**

### **1. Motivation**

Reliable projections of the Earth's climate are at the heart of scientific support for international efforts to address global change. There is increasing recognition that *reliable and useable* projections of global change require that physical climate models be extended into Earth system models (ESMs), capable of simulating key physical climate and biogeochemical processes, as well as interactions between these processes. This is motivated by biogeochemical phenomena playing a central role in both regulating the Earth's climate (Thornton et al. 2009) and in determining the overall human and natural radiative forcing of climate (Carslaw et al. 2013). Furthermore, this ability to regulate the Earth's climate may itself be sensitive to climate change (Randerson et al. 2015). The development of scientifically robust ESMs and their application to generate realistic Earth system projections are major challenges. The UKESM project directly addresses these challenges, bringing together the unique climate modelling capabilities of the Met Office Hadley Centre (MOHC) with a wealth of advanced Earth system modelling and observational capabilities from 8 NERC centres. This project will be carried out in active collaboration with the broader NERC research community to realize the development and evaluation of a world-leading ESM and ensure this model is fully applied to a range of outstanding Earth system science questions, as well as to the delivery of robust Earth system change projections to support the UK government and public.

### **2. Project summary**

The key project outcomes will be a world-leading modelling system and associated simulation-data to enable UK research to tackle the leading questions in Earth system science. The models and data developed in the project will be a national resource, supporting research both specific to this project and well beyond for the coming 5 years. The main questions that will be addressed include:

- How will the Earth system respond to future emissions of greenhouse gases (GHGs), aerosols, trace gases and land use change? Can reliable projections of this response be developed?
- How will Earth's natural carbon sources and sinks change in response to climate change and future GHG emissions? How will these changes impact allowable human GHG emissions for different target global warming levels?
- To what extent has cooling due to anthropogenic and natural aerosols balanced anthropogenic GHG warming over the industrial period? Can we accurately simulate such aerosol processes, their future role in the Earth system and thereby improve estimates of global climate sensitivity?
- What role have short-lived climate pollutants (SCLPs, e.g. black carbon, methane and ozone) played in Earth system change? What potential do SCLPs offer for climate change mitigation?
- What is the role of land use and land cover change (LULCC) in the Earth system and how will future LULCC respond to and impact on climate change, climate variability and carbon uptake?
- How will marine heat and carbon uptake change in the future? What impact will this have on global warming rates and the biogeochemistry of the global ocean? Can the processes controlling marine heat and carbon uptake be accurately simulated in ESMs?
- What will be the response of continental ice sheets to climate change? How will this impact sea-level rise and marine carbon and heat uptake? Can the key processes controlling ice sheet response to climate change be accurately represented in ESMs?
- What is the sensitivity of sea-ice to climate change and how will sea-ice changes interact with and impact physical climate processes and biogeochemical phenomena?

To provide credible answers to these questions requires: The development of an advanced Earth system modelling capability, extensive evaluation of this model and application and analysis of the model forced by plausible future GHG, aerosol and land-use scenarios. These 3 activities form the core of the UKESM project and require sustained engagement from a team of scientists with the necessary breadth of skills. In the UK this can only be met through a multi-centre effort, where NERC and the Met Office Hadley Centre (MOHC) provide the long-term foundation for such a modelling system, while also ensuring the wider body of UK science is fully engaged in the development, evaluation and scientific exploitation of such a system. This proposal brings together 8 NERC centres; NCAS, BAS, BGS, CEH, CPOM, NCEO, NOC and PML to match an equivalent commitment from MOHC to provide the multi-institutional capacity and delivery system to ensure

successful development and maintenance of a world-leading ESM, while also supporting scientific use of the model by the UK academic research community. UKESM builds on and integrates a large body of foundational science carried out at NERC centres and MOHC and is therefore an important step in realizing NERC's long-term strategic aim of developing a full Earth system model; <http://www.nerc.ac.uk/research/funded/programmes/esm/#xcollapse3>. Such a system will support advanced Earth system science research in the UK for the coming 5-10 years.

An important target for the 1<sup>st</sup> UKESM model (UKESM1) is the World Climate Research Program's (WCRP) 6<sup>th</sup> Coupled Model Intercomparison Project (CMIP6, Meehl et al. 2014). Since 1995 CMIP has provided a coordinated, multi-model framework for climate and Earth system modelling that encompasses model evaluation, model improvement and the generation of future projections. CMIP coordination enables multiple ESMs to run using common forcing data sets, simulation protocols and output standards. This has resulted in enormous leverage of international research with respect to scientific analysis of multi-model simulations, leading to major advances in our understanding of, and ability to simulate, the coupled Earth system. Coordinated, multi-model, multi-member ensembles have proven crucial in delivering robust and representative Earth system projections that sample the full range of uncertainty across projection time scales (Hawkins and Sutton 2009). Due to the complexity of the processes to be modelled and the need to sample inherent uncertainties in the future evolution of the Earth system, there is a continued requirement for a coordinated, multi-model approach to Earth system modelling and prediction. This is best met through the international coordination CMIP6 provides. This UKESM project, involving close collaboration with MOHC, will be the main activity by which the UK will contribute to this effort, in the process providing key underpinning support for the 6<sup>th</sup> IPCC Assessment Report (AR6).

### 3. Project objectives

The primary objectives of the UKESM project can be summarized as;

**O1:** To advance the understanding of and ability to simulate key Earth system processes and their future sensitivity to, and role in, global change.

**O2:** To provide robust estimates of future Earth system change to UK researchers and policymakers through the generation and analysis of an ensemble of future projections,

**O3:** To reduce uncertainty in Earth system projections by developing a set of emergent constraints on key Earth system feedbacks.

**O4:** To improve methods for assessing the realism and reliability of Earth system models through development of an open and comprehensive model evaluation tool.

**O5:** To assess and document the realism and reliability of UKESM1 using *bottom-up (process-level)* and *top-down (whole-system, coupled ESM)* evaluation.

**O6:** To further develop UKESM component models towards a 2<sup>nd</sup> UKESM model release in ~2023.

**O7:** To lead and coordinate the UK contribution to the 6<sup>th</sup> Coupled Model Intercomparison Project.

**O8:** To coordinate UK Earth system science through development of a world-leading Earth system model and provision of community support for the scientific application and analysis of this model.

How each objective links to specific project deliverables is outlined in each section of the proposal where the deliverables are presented.

### 4. Project structure and collaboration

The UKESM project is structured into 5 Research Themes (RTs, see figure 1). RT1 finalises development and release of UKESM1, including user support. RT1 will also carry out CMIP6 experiments that form the basis for the science objectives of the project. RT2 emphasizes evaluation of UKESM1, performed both at the process-level (RT2.1), and for the fully coupled ESM (RT2.2). RT3 emphasizes scientific analysis of Earth system projections, including investigation of emergent constraints to reduce uncertainty in future feedbacks. RT4 develops the component models for future UKESM, while RT5 targets improvement of fully coupled versions of UKESM.

The UKESM project will work closely with other NERC LTSM projects concerned with global climate and Earth system change. In particular ACSIS (*climate processes and predictability over the North Atlantic*), ORCHESTRA (*carbon and heat uptake in the Southern Ocean*) and LOCATE (*developing estimates and understanding of terrestrial carbon fluxes into the ocean*). Collaboration will centre on the provision of UKESM1 models and simulation data to these projects for advanced scientific analysis and conversely, the use of observations and process-understanding developed

in these projects for analysis of UKESM1 and development of UKESM2. We will also work closely with the new Horizon 2020 project CRESCENDO, coordinated by the UKESM coordinator. CRESCENDO involves 7 European ESMs, targeting improved representation and evaluation of biogeochemical and aerosol processes in ESMs. We will also collaborate with the Horizon 2020 project PRIMAVERA (coordinated by MOHC) investigating the benefits of increased resolution in physical climate models, with project findings guiding planning of UKESM2. International collaboration will also be pursued through established links focussing on key CMIP6 experiments. Such cooperation facilitates sharing of model improvements, evaluation methods and data sets, increasing the productivity of the UKESM project.

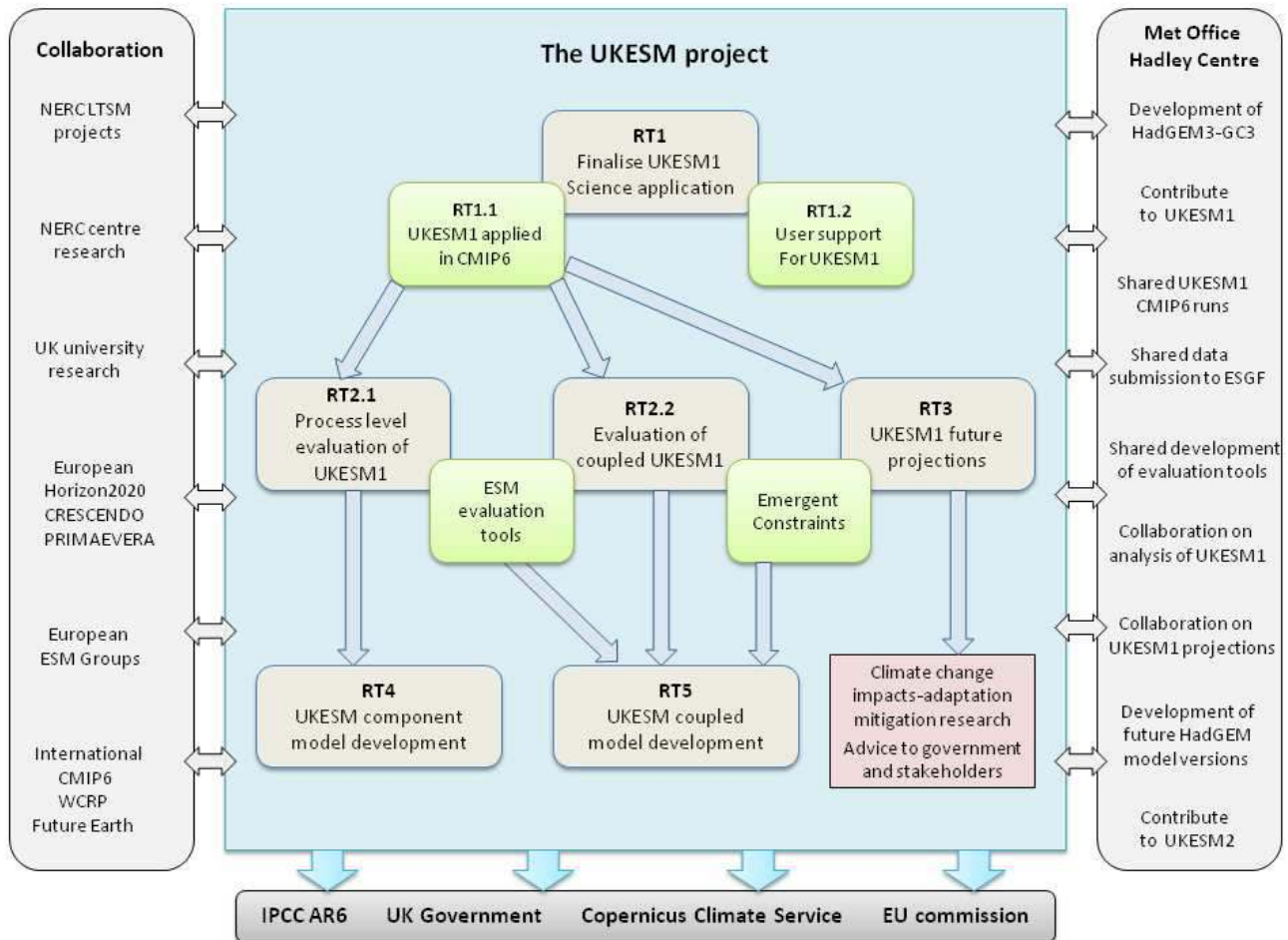


Figure 1: Schematic of the UKESM project and its relationship with MOHC (right column), UK, and international collaboration (left column), direct support to UK global change research and policy (pink boxes) and wider support to national/international climate policy and services (bottom panel). Green boxes indicate simulations, evaluation tools or user support delivered by the UKESM core group to the UK research community. RT leads are listed in each RT box.

## 5. Science and research themes

### 5.1.1 Development and community release of UKESM1: RT1.1

The UKCG is developing two versions of UKESM1 for release in autumn 2016. The 2 versions differ primarily in model resolution, referred to as; UKESM1-lr (low resolution, ~140km in the atmosphere and 1° in the ocean) and UKESM1-hr (high resolution, ~60km atmosphere and 0.25° ocean). UKESM1 is built on the physical model HadGEM3, extended through inclusion of models for; atmospheric chemistry and aerosols (UKCA-GLOMAP); marine biogeochemistry (MEDUSA); extension of the JULES land scheme to include terrestrial carbon and nitrogen cycles, dynamic vegetation, wildfires, wetlands and permafrost and an interactive ice-sheet model (BISICLES). UKESM1 user support will be shared between the UKCG and NCAS Computational Modelling Services, with a number of training workshops held to introduce new users to the model system.

***Deliverables: (O1, O8) D5.1.1: Release of UKESM1-lr (Oct 2016) and UKESM1-hr (Dec 2016)***

### 5.1.2 CMIP6: Community simulations with UKESM1: RT1.2

CMIP6 runs until 2020 and provides a set of internationally-accepted experiments to address key challenges in Earth system modelling and the provision of reliable Earth system projections. In this section we discuss those CMIP6 activities where UKESM1 will be **actively used and assessed in this project**. The overall (larger) UK contribution to CMIP6 will be realised through a close collaboration between this NERC UKESM project, MOHC and a number of UK universities. This effort is coordinated by the UKESM core group (both NERC and MOHC funded members), with a number of joint NERC/MOHC project bodies already established and working. Through the collaboration additional CMIP6 simulations, beyond those discussed below, will be made with UKESM1 and HadGEM3. Community analysis of CMIP6 simulations will build on this collaboration with the evaluation techniques described in this proposal being central to this effort.

The **CMIP-DECK** is a mandatory set of experiments designed to characterize the performance and projection sensitivity of ESMs, including a simulation of the pre-industrial period and historical past (1850-2014). The UKCG will perform the CMIP-DECK using the UKESM1 configurations listed in table 1. Combined with simulations specific to other CMIP6 Model Intercomparison Projects (MIPs), these data will be a major resource for UK science. More details on the simulations required in the CMIP-DECK and the full list of CMIP6 MIP experiments can be found at: <http://wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-cmip6-endorsed-mips>

Model Version	Date when CMIP-DECK will be run
UKESM1-lr	Sept 2016 to early 2017
UKESM1-hr	Early 2017 to end of 2019
UKESM1-is <sup>1</sup>	Late 2017 to summer 2018
UKESM1-hybrid <sup>2</sup>	Early 2018 to end of 2018

Table 1: UKESM1 configurations to be used in the CMIP-DECK and planned dates for simulations.

<sup>1</sup>UKESM1-is is the same as UKESM1-lr but includes interactive continental ice sheets (BISICLES, see sec 5.4). <sup>2</sup>UKESM1-hybrid (see sec. 5.4) uses a hybrid approach to model resolution, with the physical models of UKESM1 run at the high resolution of UKESM1-hr, while Earth system modules are interactively coupled to the physical model but run at the lower resolution of UKESM1-lr.

**C4MIP** (Coupled Carbon Cycle Climate MIP): A key difference between physical GCMs and ESMs is the latter interactively simulates the global carbon cycle, allowing ESMs to be driven by **emissions** of GHGs and aerosols, rather than predefined atmospheric **concentrations**. CO<sub>2</sub> sources and sinks can therefore respond **both** to a changing climate and changing CO<sub>2</sub> concentrations, potential resulting in reduced (increased) CO<sub>2</sub> uptake in the future and a larger (smaller) fraction of emitted CO<sub>2</sub> remaining in the atmosphere, potentially amplifying (damping) climate change. Quantifying carbon cycle feedbacks is crucial for developing robust policy advice on allowable CO<sub>2</sub> emissions and is a key emphasis of C4MIP (Jones et al., 2013).

**AerChemMIP** (Aerosols and chemistry MIP): Aerosols remain the main source of uncertainty in quantifying radiative forcing since pre-industrial times and thus severely limit estimates of global climate sensitivity (Carslaw et al., 2013). Human emissions of short-lived climate pollutants (SLCPs) such as, CH<sub>4</sub>, N<sub>2</sub>O and black carbon have contributed to climate forcing over the recent past and offer the potential for near-term climate change mitigation (Rogelj et al. 2014). Better quantifying the role of aerosols and SLCPs in the Earth system is a central goal of AerChemMIP including quantification of climate mitigation potential of alternative SLCP emission pathways.

**LS3MIP** (Land surface, snow and soil moisture MIP) and **LUMIP** (Land Use MIP): LS3MIP targets improvement in land surface, snow and soil moisture processes in ESMs and interactions between these phenomena and the terrestrial carbon-nitrogen cycle. LUMIP will investigate and quantify the impact of human-induced land use/land cover changes on past and future Earth system change.

**OMIP** (Ocean MIP): uses ocean/sea-ice models to further develop marine modelling capabilities and better quantify the role of the oceans in Earth system change. The ocean/sea-ice model of UKESM1 will be run using the 3 configurations; 1°, ¼° and ¼° with reduced-resolution biogeochemistry (the ocean component of UKESM1-hybrid, see sec 5.4) to support a full evaluation of these model versions, including documentation of their performance traceability.

**ISMIP6** (*Ice Sheet MIP*) aims to improve estimates of sea level rise through improved simulation of continental ice sheets. A second goal of the project is to investigate feedbacks between ice melt, ocean freshening and marine heat and carbon uptake. Both an offline version of the BISICLES ice model and UKESM1-is, with BISICLES interactively coupled to UKESM1, will be used in ISMIP6.

**ScenarioMIP** develops future scenarios for GHGs, aerosol and trace gas emissions and land use, based on plausible future global socio-economic development pathways (Shared Socio-economic Pathways, SSPs, O'Neill et al., 2013). These scenarios provide future emission/concentration fields to force ESMs, each matched to an underlying SSP, allowing Earth system change and the resulting impacts to be analysed in combination with consistent assumptions of socio-economic development. More detail on UKESM involvement in scenarioMIP is discussed in section 5.3.

**Deliverables (O1, O5, O7):** **D5.1.2:** *CMIP-DECK and historical simulations with UKESM1-Is complete (April 2017).* **D5.1.3:** *Simulations for C4MIP, AerChemMIP, LS3MIP, LUMIP, OCMIP and ISMIP6 using UKESM1-Is complete (Jan 2018).* **D5.1.4:** *ISMIP6 simulations with UKESM1-Is complete (mid-2018).* **D5.1.5** *CMIP-DECK and historical simulations with UKESM1-hybrid complete (Oct 2018).* **D5.1.6:** *Key experiments in D5.1.3 repeated with UKESM1-hybrid (March 2019).* **D5.1.7:** *Subset of CMIP-DECK and historical runs with UKESM1-hr (mid 2019)*

## 5.2 Analysis and evaluation of UKESM1: RT2

To increase confidence in ESMs it is important they are carefully evaluated against observations. Evaluation of the *biogeochemical* components of ESMs lags behind *physical climate process* evaluation. Several reviews highlight the importance of both “*top-down*” and “*bottom-up*” evaluation in ESM improvement (Foley et al 2013). *Top-down* evaluation focuses on full ESMs and *whole-system* outputs, such as average fields of temperature, carbon stores, aerosol optical depth. *Top-down* evaluation aims to ensure models “*get the right answer*”. *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 be achieved through compensating model errors which may mean models evaluate well for the present-day but their sensitivity to a changed forcing, such as increasing GHGs, may be incorrect. Hence the need for *bottom-up* evaluation which tests models at the process level, ensuring model components have the right sensitivity to a range of input drivers. *Bottom-up* (process-level) evaluation ensures models deliver “*the right answers for the right reasons*”. Both approaches are addressed in RT2.

### 5.2.1: Process level evaluation of UKESM1 component models. RT2.1

We will evaluate natural aerosols in UKESM1 using AerChemMIP, CMIP DECK and historical runs. One difficulty in the evaluation of natural aerosols is that observed aerosol is almost always a mixture of natural and anthropogenic components. It is therefore important to develop metrics that identify conditions which are as pristine as possible, where natural aerosol dominates. A combination of metrics will be tested to define such regions based on trace gases (e.g. CO), black carbon aerosol etc. Metrics will be applied both to UKESM1 and observations to generate a data base of natural aerosol states. Parameters will be compared across these states (e.g. aerosol size, number, mass, seasonal cycle and interaction with clouds and radiation). Evaluation will also consider exchange processes between model components (e.g. marine and terrestrial emissions, dust emission, deposition). Evaluation targets both total aerosol and individual aerosol components (sulphate, nitrate, black carbon, dust). The Global Aerosol Synthesis and Science (GASSP) project, along with satellite data (e.g. ESA-CCI) will form the main evaluation data.

Evaluation of terrestrial processes will use simulations from the CMIP-DECK, historical, C4MIP, LS3MIP and LUMIP experiments. We will evaluate the uptake and release of CO<sub>2</sub> and other GHGs (e.g. CH<sub>4</sub>, N<sub>2</sub>O) by soils and vegetation, terrestrial carbon storage and the fraction of stored carbon that is labile. Both offline JULES-CN and coupled UKESM1 simulations will be analysed. The distribution of simulated vegetation types and their response to nutrient limitation, temperature and soil moisture will be assessed. Vegetation may acclimatize to future climate states and change its photosynthetic rate. This sensitivity will be analysed in JULES-CN. Data to be used include: (i) Satellite observations of fluorescence (for photosynthesis), NDVI (for leaf area index), above ground biomass (for vegetation carbon). (ii) Fluxnet data (e.g. CO<sub>2</sub>, CH<sub>4</sub>, surface fluxes). (iii) Estimates of below ground carbon stores. (iv) Land cover data (GLOBCOVER, GLOBALBEDO).

Ocean evaluation emphasizes key biogeochemical processes such as; primary production and carbon export, air-sea exchange of CO<sub>2</sub> and DMS, oxygen minimum zones and plankton



community structure. Evaluation will use coupled simulations made in C4MIP, CMIP-DECK and the CMIP6 historical, as well as ocean-only OMIP runs. We will utilise (and further develop) existing metrics that compare model and observations in space and time (Stow et al 2009). A focus will be on biogeochemical responses to physical ocean drivers (e.g. ocean mixing, water mass formation, shelf-sea to deep ocean exchange, coastal upwelling, boundary currents, sea-ice variability). We will assess how these phenomena and their impact on marine biogeochemistry differ across model configurations used in OMIP. For observations, we will use a range of state variables (temperature, salinity, nutrients, oxygen, carbon), satellite data for; chlorophyll-a, primary production and plankton structure, as well as long-term observatories and process-focused observations.

Sea ice will be evaluated using CMIP-DECK, historical and OMIP simulations and the SIMIP diagnostics from CMIP6. Metrics for; ice concentration, extent, motion, below-ice ocean mixed layer depth will be developed. CryoSat-2 will be used to assess sea ice thickness. Sea-ice budget terms will be assessed following Holland and Kwok (2012) combining satellite and reanalysis data. Ice sheet surface mass balance (SMB) will be evaluated in UKESM1 CMIP-DECK and ISMIP6 simulations, against existing regional climate model simulations. For Greenland we will compare model melt area with satellite estimates. Offline and coupled BISICLES will be run for Greenland and Antarctica. The ice sheet response will be evaluated using satellite observations (e.g. rates of mass change, velocity fields and grounding line). Analysis of sub-ice-sheet heat and freshwater fluxes in UKESM1 will focus on their interaction and forcing of Antarctic deep water formation.

***Deliverables (O1, O4, O5, O8): D5.2.1: Papers evaluating; UKESM1 chemistry-aerosol-climate interactions (2017-2020), D5.2.2: UKESM1 terrestrial biogeochemical-climate processes (2017-2020), D5.2.3: UKESM1 marine biogeochemical-climate processes (2017-2020), D5.2.4: UKESM1 cryosphere-climate interactions (2017-2020).***

### **5.2.2 Evaluation of coupled versions of UKESM1, RT2.2**

Evaluation of the coupled UKESM1 emphasizes *whole-system output* with variables averaged to highlight; climatological behaviour (e.g. annual cycle), forced trends (e.g. over the industrial period) or unforced variability (e.g. multi-decadal). Model data will be compared to equivalent-averaged observations to determine parameters/regions/modes where UKESM1 is poor or exhibits robust accuracy. A key aspect in our evaluation is recognition that increased model complexity/realism, through inclusion of new or more advanced process descriptions, increases the possibility of coupled error growth but also means models will be more capable of realistically representing the Earth system response to future GHG emissions. This needs consideration when deciding the suitability of a model for making future projections. Evaluation will focus on the CMIP-DECK (for multi-decadal variability) and CMIP6 historical runs (for trends over the past 150 years and direct comparison to observations), as well as the C4MIP pre-industrial and historical simulations where emissions of GHGs will be used to force UKESM1 as opposed to atmospheric concentrations in the standard CMIP-DECK and historical simulations.

Interactions between the physical climate and biogeochemical processes will be evaluated for a range of time and spatial scales; (i) The annual cycle of physical variables (e.g. temperature, ocean mixed layer depth, snow cover) and biogeochemical processes (e.g. terrestrial and marine carbon uptake/release, permafrost melt). (ii) Spatially discrete climate phenomena, such as ocean boundary currents and coastal upwelling and carbon/heat uptake. (iii) Modes of natural climate variability (e.g. El Nino Southern Oscillation, Pacific Decadal Oscillation) and biogeochemical phenomena (e.g. carbon uptake/release, aerosol forcing). (iv) Synoptic variability (e.g. anticyclonic blocking, ocean eddies) and links to vegetation growth/decay and marine biological productivity.

A key difference between physical climate models and ESMs is the number and complexity of interactions between model components and the potential for biases in one component to drive errors elsewhere. It is essential to evaluate the nature and strength of these interactions. As an example, simulated vegetation is sensitive to biases in soil moisture and precipitation. Soil moisture deficits can lead to a die-back of vegetation and large increases in bare soil, resulting in excess dust emissions, with potential feedbacks on the physical climate and marine biology. Similarly, UKESM1 has the capability to predict methane emissions from wetlands and permafrost and feed these into UKCA chemistry model. Interactive use of these emissions is only feasible if they are realistic and if UKCA simulates a realistic methane lifetime. Model biases in methane

amounts can feedback on the physical climate through longwave radiative forcing. A range of such interactions will be analysed in UKESM1 to ensure scientific robustness of the coupled model.

The ability to reproduce the evolution of key parameters over the historical period is important to increase confidence in model projections. A focus will be on the evaluation of climate parameters that are *prescribed* in physical climate models but *interactively simulated* in ESMs. This includes; atmospheric GHGs and SLCPs, aerosols and vegetation. In-situ and satellite observations, when of sufficient duration and accuracy, will be used to assess such parameters.

The new field of *emergent constraints* uses multi-model ensembles to identify relationships between present-day observable quantities and future climate response (e.g. Hall and Xu 2006, Cox et al., 2013). By selecting models which best agree with observations for these quantities, the inference is that these models point towards the more likely (e.g. realistic) future response. Identifying new emergent constraints is beyond the scope of this project. Such work will be undertaken in CRESCENDO by partners at MOHC, NOC and the University of Exeter. We will collaborate with CRESCENDO and aim to apply identified constraints to UKESM1 projections, as well as use such constraints in the development cycle of future UKESM models.

**Deliverables (O1, O3, O5, O8):** **D5.2.5:** *Papers evaluating UKESM1-Ir (2017-2020)* **D5.2.6:** *Papers evaluating UKESM1-hybrid and UKESM1-hr with reference to UKESM1-Ir (2018-2020).* **D5.2.7:** *Papers describing use of emergent constraints in model development (2021)*

### 5.3 Earth system projections with UKESM1: RT3

With respect to Earth system models, the primary interest of policymakers and the public are reliable projections of the Earth's climate and associated socio-economic impacts. To address this we apply UKESM1 within ScenarioMIP forced by a range of GHG, aerosol and aerosol precursor emissions, as well as LULCC scenarios. ScenarioMIP repeats the main Reference Concentration Pathways (RCPs) of CMIP5 (RCP2.6, 4.5 and 8.5) with each RCP now linked to a number of underlying SSPs. It also includes a number of new policy-relevant "gap" scenarios (RCP3.7 and RCP7.0) and an "overshoot" scenario based on RCP2.6. RCP3.7 and 7.0 are of interest to assess "impacts-avoided" by comparing resultant impacts to those from RCP2.6 and RCP8.5 respectively. The "overshoot" scenario assumes reductions in GHG emissions required to begin by 2020 in RCP2.6, do not occur until ~10-20 years later, reaching the same emissions as RCP2.6 by 2100. As a result of the emission "overshoot" there will likely be an "overshoot" in global warming with implications for regional impacts and adaptation options. ScenarioMIP also investigates: (i) The potential for near-term climate change mitigation from emission reduction of key SLCPs (with AerChemMIP). (ii) The potential for LULCC to mitigate/adapt to Earth system change (with LUMIP). (iii) The sensitivity of natural carbon source/sinks to future global change and implications of this on allowable human CO<sub>2</sub> emissions (with C4MIP). The latter will be addressed by comparing UKESM1 projections driven by prescribed atmospheric CO<sub>2</sub> concentrations (*natural carbon cycle changes cannot influence atmospheric CO<sub>2</sub>*) with the projections driven by emissions of CO<sub>2</sub> (*natural carbon cycle changes influence the fraction of CO<sub>2</sub> remaining in the atmosphere*).

UKESM1-Ir will be used to generate an ensemble of projections in scenarioMIP. Knowledge from these, combined with the analysis of resulting climate-impacts, will provide important support to UK policymakers. The 3 scenarios addressing; near-term SLCP mitigation, land-use mitigation and natural carbon cycle feedbacks will be simulated with both UKESM1-Ir and UKESM1-hybrid to assess whether higher model resolution affects the Earth system response. For key projections, data will be saved to allow subsequent downscaling over the UK, to generate high-resolution national projections consistent with the driving UKESM1 projections. Downscaling will be performed external to the project, led by MOHC. UKESM1 projections, with the full ScenarioMIP ensemble, will be used to develop a set of emergent constraints on future Earth system feedbacks with an aim to constrain the spread in future projections and direct future model development.

**Deliverables (O1, O2, O3, O7):** **D5.3.1:** *ScenarioMIP projections with UKESM1-Ir (late 2017).* **D5.3.2:** *Projections addressing mitigation of SLCPs and LULCC (mid-2018)* **D5.3.3:** *Concentration and emission driven projections with UKESM1-Ir (Dec 2018).* **D5.3.4:** *Key projections repeated using UKESM1-hybrid (spring 2019).* **D5.3.5:** *Papers analysing scenarioMIP projections with UKESM1-Ir (2018-2020) and contrasting UKESM1-Ir and UKESM1-hybrid projections (2019-2021)* **D5.3.6:** *Papers on climate change mitigation from SLCPs and LULCC (2018-2020)* **D5.3.7:** *Papers on the response of carbon sources and sinks to Earth system change (2018-2020).*

#### 5.4 UKESM component model development: RT4

Development of UKESM component models has 2 primary targets; (i) implementation of key improvements to UKESM1 and (ii) longer-term development of a 2<sup>nd</sup> version of UKESM.

Due to its high resolution UKESM1-hr is computationally expensive, the main cost being the UKCA-GLOMAP chemistry-aerosol scheme and MEDUSA ocean biogeochemistry. To reduce this cost we are developing a facility to run UKCA-GLOMAP interactively coupled to the UM atmosphere, but at a lower resolution (referred to as UKESM1-hybrid). The reduced-resolution UKCA-GLOMAP will be driven by the high-resolution physical climate every model time step and feedback chemistry and aerosol variables each time step to influence the evolution of the physical model, offering a computationally viable approach for both high physical model resolution and the desired chemistry and aerosol complexity. A similar reduced-resolution approach is under development for the advection of biogeochemical tracers in the NEMO ocean model. UKESM1-hybrid is targeted for release and application to key CMIP6 simulations in early 2018.

The future response of plant productivity to climate change is a key uncertainty in ESMs mainly due to uncertainty in the temperature sensitivity of photosynthesis and plant respiration. We will improve the temperature response of photosynthesis in JULES-CN and also represent the thermal acclimation of vegetation. Future emissions of N<sub>2</sub>O from agricultural land and CH<sub>4</sub> from wetlands are both highly uncertain (Ciais et al., 2013) yet important GHG sources. An improved model of soil carbon and nitrogen exists in JULES-CN, but still neglects several key processes. We will develop an improved version of this model accounting for agricultural input of fertilisers and wetland hydrology, targeted for UKESM2. In the future, plant productivity may be limited by phosphorus availability. To address this we will develop a model of soil and vegetation phosphorus for a JULES-CNP model. Finally, an improved representation of dry deposition between JULES-CN and UKCA will be developed.

The ocean component of UKESM2 is anticipated to be  $1/12^\circ$  resolution allowing improved representation of shelf seas, coastal upwelling and ocean eddies. To capitalize on these increased capabilities we will develop a number of parameterizations currently not available in UKESM1 including; the ocean methane cycle, including seafloor stability of methane clathrates, the ocean N<sub>2</sub>O cycle and river to ocean fluxes of key biogeochemical variables. Shelf-sea areas include unique processes tightly coupled to pelagic systems. To represent such processes we will improve the benthic model in UKESM1 to resolve the burial of carbon, consumption of oxygen, recycling of nitrogen and silica and production of CO<sub>2</sub> and N<sub>2</sub>O. These developments will also facilitate improvements to the model iron cycle which is a key constraint on the marine carbon pump.

A key upgrade to UKESM1 is interactive coupling of the ice sheet model BISICLES (UKESM1-is). In this model, the ice-sheet grounded area, topography and thickness are allowed to evolve making it possible to simulate the elevation feedback of melting ice sheets on SMB. A prognostic ice sheet grounding line will facilitate further investigation of marine ice sheet instability, a major uncertainty in ice sheet change and sea-level rise. Many key ice shelves will not be resolved in UKESM1. A focus will therefore be on the parameterization of sub-grid scale ocean circulation and cavity ice sheet melt. A new melt pond parameterisation (Flocco et al, 2012), shown to have a leading order impact on the mass balance of Arctic sea ice, combined with anisotropic sea ice mechanics (Tsamados et al, 2013), will be developed for use in UKESM2.

The Global Volcano Model (GVM) is a programme to create and sustain a comprehensive information platform on volcanic hazard and risk, led by BGS. GVM provides systematic evidence, data and analysis of volcanic hazards and risk on global and regional scales. GVM is developing capabilities to anticipate future volcanism and its consequences. Inclusion of the effects of volcanism is a key component in Earth system models. We plan to scope and initiate the interfacing of GVM to UKESM, enabling a world-leading capability to translate the best assessments of volcanism into climate impacts. This will be facilitated by visits between the BGS GVM team to the UKESM team and by joint climate/volcanology workshops.

**Deliverables (O1, O6, O8):** **D5.4.1** Release of UKESM1-is (mid-2017) and documentation paper (late 2017). **D5.4.2:** Papers analysing sea-level and ice sheet projections in UKESM1-is (2018-2020). **D5.4.3** Release of UKESM1-hybrid (Jan 2018) and documentation papers (mid-2018). **D5.4.4** Terrestrial biogeochemical improvements implemented in JULES-CN and initial performance documented (2018-2021). **D5.4.5** Marine biogeochemical improvements implemented



in MEDUSA-ORCA and initial performance documented (2018-2021). **D5.4.6** Sea-ice improvements implemented in CICE-ORCA and initial performance documented (2018-2020). **D5.4.7** A fully scoped plan for implementing an interface between GVM and UKESM (2020).

## 5.5 Towards UKESM2: RT5

Two updates are planned after the formal UKESM1 release; (i) UKESM1-is will include interactive continental ice sheets. (ii) UKESM1-hybrid (see sec 5.4). While no further formal releases are planned, component model developments in RT4 that have a major impact on the quality of UKESM1 may be considered for inclusion in a model update in ~2019.

We aim to develop a new UKESM2 model for scientific application by ~2023, to coincide with a probable CMIP7 and IPCC AR7. Component model development will begin at the outset of the project in RT4 and will also be pursued external to this project at NERC centres and MOHC. UKCG scientists will begin work on a coupled UKESM2 from ~mid-2019. The Unified Model (UM) atmosphere of HadGEM will be radically restructured on the timescale of UKESM2, with a new dynamical core based on the NERC-MOHC GungHo collaboration. Preparation of the UM for this new dynamical core and to take advantage of new HPC architectures requires a fundamental restructuring of the UM computational code with significant implication for UKESM component models. Initial work will focus on ensuring UKCA-GLOMAP is compatible with the GungHo dynamics and new UM code infrastructure. In the ocean we aim to use the  $1/12^\circ$  global version of NEMO. To maximize benefits UKESM ocean biogeochemical modellers will work with the Joint Ocean Modelling Program (JOMP) to ensure future model developments consider both dynamical and marine biogeochemical requirements. To realize the benefits of future HPC systems, UKESM2 will need to efficiently utilise large amounts of compute cores ( $\sim 10^5$ - $10^6$ ), putting increased demand on component model parallelization, concurrency of component model operations and efficient model coupling. The UKCG will work with MOHC and NERC on these critical areas.

**Deliverables (O6, O8): D5.5.3: Preliminary version of UKESM2 available (mid 2021).**

## 6. Project Management

The project coordinator (PC) will be Colin Jones, present head of the UKESM core group. He will be supported by a project manager (PM, 20% FTE) who will have responsibility for day-to-day running of the project. Due to the size of the UKESM user network, the project will employ an integration scientist (30% FTE) to maintain a dialogue between the project and both the NERC research community and MOHC. This will be critical to ensure project developments fully feed into, support and benefit from research at UK universities, NERC centres and MOHC. The PC will lead on project dissemination. A project steering committee (SC), composed of 1 member from each of partner institutes, will be the main decision-making body of the project and be responsible for reviewing progress, forward-planning and developing solutions to any delays. The PC will be the first point of contact with NERC. The project will report to a NERC-appointed oversight body and will appoint an external science advisory board. The project will meet once per year at a science workshop, with MOHC members of the UKESM core group and other key MOHC scientists invited to attend. Other targeted workshops will be organised as required through dialogue with the PC and PM. The UKESM core group will continue to meet ~once per month.

## 7. Wider relevance of the project

NERC support for the UKESM project matches a similar level of support from MOHC for the development and community-support of UK Earth system models. This project integrates a large number of research activities carried out at NERC centres, MOHC and UK universities, focussing these onto the development and evaluation of a world-leading Earth system model, addressing one of the main recommendations of the joint NERC/MOHC strategy on Earth system modelling:

*“If we are to maintain UK leadership in the field of Earth system modelling it is essential the UK ESM community works together in a coordinated way that more effectively exploits the strengths of the Met Office and the NERC community.”*

This integration, combined with a core model group, will enable UK science to deliver world-class research and knowledge-support to UK government and the public. The UKESM project is a fundamental component of the planned UK contribution to CMIP6 which is coordinated by the UKESM core group and involves strong collaboration with MOHC, NERC centres and UK

universities. Without this project, the UK contribution both to CMIP6 and IPCC AR6 will be significantly diminished, consisting solely of MOHC physical climate model simulations.

Future projections made with UKESM1 will provide underpinning data and knowledge for research into climate change impacts, adaptation and mitigation. In collaboration with MOHC, projections made by UKESM models will be downscaled over the UK and adjacent waters generating a consistent set of global to national Earth system projections that sample a plausible range of future socio-economic development pathways. The resulting high-resolution projections will be a valuable resource for national and regional planners, UK business and the public. Through this project and the close collaboration with MOHC, NERC science will make a major contribution to national and international efforts to understand, prepare for and mitigate Earth system change.

The UKESM1 model and associated simulation-data will be a major facility for UK Earth system science over the coming 5-10 years, including use of a world-leading ESM or university research and training. The development of a 2nd version of UKESM, initiated within the project and including improved process-descriptions and increased model resolution, will ensure long-term continuity for advanced Earth system modelling in the UK. Such long-term planning is critical to keep the UK at the forefront of international efforts in Earth system modelling and to ensure continued delivery of the best possible policy and public advice on Earth system change. To ensure strong engagement with the broader UK research community, annual community workshops will be held to provide updates on UKESM model development, evaluation and science applications. The workshops will aim to both provide information to the research community while also working to engage members of this research community in further development and exploitation of UKESM models.

## 8. Project scalability

**80% funding:** NERC presently funds 10 members of the UKESM core group. This proposal, if fully funded, will increase this to 13. If the project receives only 80% funding every effort will be made to keep the core group at the intended 13 scientists. Three areas have been identified for reduced effort if funding is only 80%: (i) Reduced development of UKESM2, including the component models. This will delay the availability of UKESM2, potentially compromising the UK leading position in Earth system modelling. (ii) Reduced size and reduced analysis of the ensemble of UKESM1 projections made in scenarioMIP. While still allowing delivery of useful knowledge on Earth system change, reduction in the ensemble size of future projections will lead to a decrease in the robustness of science and policy information provided by the project. (iii) There will be risk to the use of the higher resolution model, UKESM1-hybrid, in CMIP6. UKESM1-hybrid is a unique approach to Earth system modelling that would cement UK research at the forefront of CMIP6.

**120% funding:** A key focus of the project is an in-depth, process-level evaluation of UKESM1 simulations and projections. Careful evaluation of the range of processes represented is the only way to fully evaluate an ESM and gain confidence in model projections. With respect to ESMs, process-level evaluation is still in its infancy compared to physical climate models. While a large amount of effort is required to make progress, there is enormous opportunity for cutting-edge science to be performed. At 100% funding the majority of our effort in process-level evaluation will concentrate on UKESM1 models. With 120% funding we will extend this to include other leading ESMs, building on our strong collaborations with European and North American ESM groups. Such a multi-model evaluation will significantly increase the robustness of science findings and lead to high-profile publications from the project in advance of IPCC AR6. With increased funding, we will also expand the range of processes evaluated and observational data used in this work.

## 9. References

**Carlsaw K. et al.** *Nature*, 503, pp.67-71, 2013. **Ciais, P. et al.** *Contribution of WG I to the IPCC AR5 2013*. **Cox, P. et al.** *Nature*, 494, 341–344, 2013. **Eyring V. et al.** *Submitted to Geosci. Model dev*, 2015. **Flocco D. et al.** *J. Geophys. Res.* 117, C09032, 2012. **Foley A. et al.** *Biogeosciences* 10, 8305-8328, 2013. **Hall, A. & X. Qu.** *Geophys. Res. Lett.*, 33, L03502, 2006 **Hawkins E & R. Sutton**, 2009: *Bull. Am. Met. Soc.*, 90, 1095–1107. **Holland P. & R. Kwok** *Nature Geoscience* 5, 872-875, 2012. **Jones C. et al.** *J. Climate*, 26, 4398–4413, 2013 **Meehl, G. et al.** *Eos Trans.* 59, 77, 2014. **O'Neill B. et al.** *Climatic Change* 122, 387-400, 2014. **Randerson J. et al.** *Biogeosci* 29, 744-759, 2015. **Rogelj J. et al.** *PNAS* 111, 16325-16330, 2014. **Stow, C. et al.** *J. Mar. Sys.* 76, 4–15, 2009. **Thornton, P. et al.** *Biogeosci*, 6, 2099-2120, 2009. **Tsamados M. et al.** *J. Geo Res.*, 118, 91 107, 2013