NERC Strategy for Earth System Modelling

1. Introduction

Recommendation 1: Earth System Modelling (ESM) is critical to the delivery of NERC's strategy. The UK community should maintain our status as world leaders in ESM through a firm commitment to a UK-led family of Earth System Models to address both science and policy questions throughout the coming decade. Both component submodels and full ESM configurations require stably supported development teams if they are to deliver the required progress.

1.1. This proposal for a NERC Strategy for Earth System Modelling has been commissioned by NERC and written by a team of experts (the ESM Strategy Group) drawn from NERC centres, universities and the Met Office. It focuses particularly on NERC's proposed contribution to a National Strategy for ESM, to be implemented in partnership with the Met Office and other key stakeholders, to ensure that the UK remains internationally competitive in this field.

1.2. Earth System Modelling (ESM) is critical to the delivery of NERC's strategy, particularly for the Climate System and Earth System Science themes.

1.3. NERC's strategic goal is:
To deliver world-leading environmental research at the frontiers of knowledge:

- enabling society to respond urgently to global climate change and the increasing pressures on natural resources;
- contributing to UK leadership in predicting the regional and local impacts of environmental change from days to decades; and
- creating and supporting vibrant, integrated research communities.

1.4. ESM is a key component in the delivery of all of the elements of this goal. At shorter timescales predictions will form part of the proposed UK climate service to a wide range of public and private sector organisations. At longer timescales they are critical to the formation of evidence-based policy on climate change mitigation and adaptation. ESM is also an essential tool for answering many of the stimulating scientific challenges posed by the history of the Earth system, such as explaining the natural changes recorded in palaeoclimate records, and improving knowledge of the interactions between the evolution of life and the Earth. The evolution of the climate system is strongly influenced by a range of physical processes and feedbacks that are only beginning to be incorporated into global models. The complexity of such models is increasing rapidly, and if we are to maintain the UK's leadership in this area it is essential that the scientific community works together in a coordinated way so that developments across the range of Earth system components can be integrated in a timely way into 'operational' predictive models.

1.5. Model development is a long-term strategic activity, and much of the required work to support models as a community resource does not produce immediate, high-visbility outputs such as published papers. However the models produced are key underpinning tools that enable scientific outputs from the wider community. Development of ESM requires stable modelling teams, and future support must be evaluated against this strategic perspective.

1.6. Given NERC's aspirations to contribute to continuing UK leadership in climate and environmental prediction, to provide actionable scientific advice on mitigation, adaptation and

related issues, this demands an over-arching strategy that is visible and widely understood in the community.

1.7. It is proposed that the strategic priorities for the UK in ESM are:
- The UK must maintain and develop its world leading brand of ESM.
- The NERC-Met Office partnership in ESM must be developed and strengthened.
- The link between Numerical Weather Prediction and climate modelling needs to be strengthened.
- Convergence is required on a framework that allows a wide range of ESM experiments to be undertaken consistently.
- Development is needed of a structure which facilitates rapid progress by new users and assists innovation from national and international partners.

Objective of this document

1.8. The objective of this document is to define a NERC Strategy for Earth System Modelling that will provide a framework for identifying and selecting the ESM activities that will be supported by NERC in the context of both its National Capability and its Research Programmes.

1.9. The scope of this proposed strategy covers Earth System Models of the physical climate system and biological and chemical feedbacks on to the climate. This strategy therefore does not include other important areas such as climate impacts, local and regional models, weather forecasting, socio-economic modelling, Earth core/plate tectonics and the mesosphere.

1.10. Earth System Modelling is a dynamic developing discipline. It is not the intention of NERC to prescribe a limited list of models that it will support; NERC will fund research using any model where there is a clear scientific justification for its use. However where the aim is to enhance the broader UK capability in Earth System Modelling this strategy aims to provide a focus and clear direction for the development of this capability.

2. Development of Earth System Models

Recommendation 2: NERC should continue to play a leading role in developing ESMs with higher resolution, and with lower computational cost, than current 'operational' configurations. Such ESMs will be related to and will inform the 'operational' ESM configurations, which will continue to have a Met Office lead. NERC will seek to pursue this strategy as part of a wider ESM programme with the Met Office and other partners.

2.1. NERC will contribute to the ongoing development of a world leading UK-based suite of coupled ESMs (a current UK scientific strength).

2.2. The overall UK strategy and governance for developing specific ESM configurations will be agreed between NERC, the Met Office and other contributing stakeholders. The Joint Weather and Climate Research Programme (JWCRP) will play a key role in the governance of the UK's strategic ESM. Outstanding issues such as the governance framework must be agreed as a matter of urgency.

2.3. The range of problems studied by NERC scientists demands a very broad span of model resolution and capability. The long-term aspiration should be to have a single family of models meeting all these needs, with traceability of processes between configurations of different levels of resolution/complexity. It is proposed that NERC will play a leading part in

exploring the role of increasing resolution in ESMs, beyond current 'operational' resolutions, and also in developing a lower cost ESM configuration suitable for longer timescales, large ensembles, studies targeting individual processes, and testing of new component models in an ESM context. The development of the high resolution and low cost model versions would be a logical development of the work of the current HiGEM and QESM teams respectively. Such model configurations will inform the next generation of 'operational' ESM configurations, which will continue to have a Met Office lead. Agreement of the NERC focus in this area is time-critical in some cases, where the support of these models is currently dependent on time limited grants. The entire spectrum of models needs to be governed by an overarching development plan, to be owned by all partners.

2.4. Individual strategies for component sub-models have been developed and are summarised below. The need to run efficiently across the full resolution/complexity spectrum should be built into the design requirements of all component sub-models. The component sub-models must be linked and run as ESMs under a new UK ESM framework (see section 3). The ESM Strategy Group believes that the development of a new ESM Modelling framework is essential for the effective and efficient use of Earth System Models in the future. This must be developed in partnership between NERC and the Met Office.

2.5. An underlying issue is to ensure that developments are able to exploit emerging supercomputer technologies and related developments such as grid and cloud computing.

3. UK ESM Framework

Recommendation 3: NERC and the Met Office should collaborate on the development of a new Earth System Modelling framework.

3.1. The UK requires a model framework for ESMs which is readily configurable and sufficiently flexible to enable the construction and running of ESMs and their component sub-models by a wide range of research and operational users. Key features are ease of use, ease of modification, flexibility and computational efficiency. However it must also be recognised that simultaneous meeting of all these requirements may be challenging.

3.2. The software framework should be developed in collaboration with the Met Office and other stakeholders, with governance and ownership to be negotiated between those stakeholders. Ongoing engagement should be maintained with international discussions on establishment of modelling frameworks, so that the UK community remains well placed to influence and exploit such developments.

3.3. The software framework and functionality should as far as possible be independent of any specific sub-models. By contrast, the current version of the Met Office Unified Model encompasses both a ESM framework and an atmosphere component, which should be separated. The UM provides the present UK ESM framework. Now is an opportune time to start development of the new framework in parallel and close association with the work on a new atmospheric dynamical core able to exploit fully emerging supercomputer technologies (see paragraph 4.2).

3.4. Recognising that progress towards the desired framework will be evolutionary, there is a need rapidly to establish and implement a plan to deliver interim improved usability of the Met Office Unified Model, and the sharing of the latest ESM development versions, over the short to medium term.

Development of component sub-models

4. Atmospheric dynamics

Recommendation 4: The 2009 TAP action to build a new atmospheric dynamical core to the Unified Model should be the focus of development in this area.

4.1. The Met Office Unified Model will continue to be the strategic atmospheric dynamics model for both climate and weather prediction. Improving the resolution and performance of the model is becoming severely constrained because of its ability to scale to take full advantage of the current generation of highly parallel computers. It is therefore imperative that the UK develops a new dynamical core and code structure in order to exploit the emerging super-computer technologies.

4.2. NERC has already committed through the 2009 Climate Theme Action Plan, and in partnership with the Met Office and STFC, to an investment in research aimed at identifying the next generation dynamical core. This can form the beginning of the required next generation model development team. This needs to integrate with the development and adoption of an up to date and internationally recognised model framework.

4.3. Little or no further development of the existing dynamical core within the UM should be undertaken within the NERC community.

5. Atmospheric physics

Recommendation 5: The atmospheric physics element of the Unified Model should continue to be developed and enhanced in order to ensure that full advantage is taken of the potential for increased resolution, including the resolution of processes not previously modelled.

5.1. A fundamental issue for atmospheric modelling is to represent optimally the separation between processes which are resolved and modelled explicitly and processes which occur on the sub-grid-scale and hence are parameterised. The increasing resolution of models means that some processes which were once entirely parameterised are now partially resolved (e.g. convection) while other processes will remain parameterised for a longer time (e.g. aerosol-cloud interactions, cloud microphysics).

5.2. Physical process understanding itself is in many areas still not sufficiently good for accurate representation in models and this remains a major focus of activity. Examples include cloud micro-physics (especially ice), cloud-aerosol interactions, stably-stratified turbulence and surface exchanges.

5.3. Atmospheric physics parameterisations must be based on algorithms that are suitable for efficient execution on massively parallel computer architectures. Hence they will need to be designed and coded taking into account the design of the massively parallel dynamical core discussed in paragraphs 4.1 and 4.2.

6. Atmospheric composition

Recommendation 6: The UK Chemistry and Aerosol (UKCA) model should be the platform for the modelling of atmospheric composition within ESMs.

6.1. Development of UKCA (UK Chemistry and Aerosol) model should continue to be undertaken to ensure it remains as one of the world leading atmospheric composition model for ESMs and also the model of choice for Met Office and the UK academic community.

6.2. Attention needs to be given to developing well-founded surface exchange schemes (terrestrial and marine). The chemistry and aerosol schemes available to UKCA focus on centennial scale problems. There is a need to develop a range of traceable schemes ranging from very detailed schemes for process, local or short-time scale problems through to schemes suitable for very long palaeo-scale integrations.

6.3. Off-line chemical transport models (CTMs) will remain a key component of an overall Earth System modelling effort in composition, being powerful testbeds for new schemes but also allowing individual process studies to be carried out in greater detail than in ESMs. There should be a consolidation of current effort to produce a single UK CTM with a clear view to future development consistent with the overall framework plan.

7. Land surface

Recommendation 7: The Joint UK Land Environment Simulator (JULES) should remain the land surface model of choice within NERC for ESM and be developed to include additional components.

7.1. The Joint UK Land Environment Simulator (JULES) should remain the land surface model of choice within NERC for ESM and the land component of a NERC/Met Office Earth System Modelling System. The aim is to maintain JULES as a world leading land surface model.

7.2. The interface of JULES to the other components of the Earth System (notably atmospheric chemistry, land ice and ocean biogeochemistry) needs to be developed. A number of components of JULES will need to be included or developed further, for example permafrost, groundwater, macronutrients and vegetation dynamics.

7.3. New global and regional datasets are needed to develop and benchmark JULES.

8. Ocean dynamics and physics

Recommendation 8: NEMO will continue to be the model for ocean dynamics and physics in the medium term; the longer term strategy is to develop a model that can be applied seamlessly to both the open ocean and coastal seas.

8.1. The UK strategy for ocean modelling will continue to focus on the NEMO (Nucleus for European Modelling of the Ocean) system for the medium term.

8.2. Models with generalised vertical grids (such as HyCOM) should continue to be developed in the short-to-medium term to enable the UK to investigate “full-physics” climate models which are structurally different from those at the Met Office, and to inform decisions about implementation of such coordinate systems in NEMO.

8.3. The UK should be supportive of, and responsive to, the development of emerging modelling technologies (e.g. unstructured grid models such as FVCOM and ICOM), and assist their passage to operational models if they are proven to provide a better long term development path.

8.4. The UK should develop a general ocean model that can be seamlessly applied to the open oceans and adjacent coastal seas. The Next Generation Climate and Weather Prediction action in the 2009 Climate System Theme Action Plan has a specific element to develop a 10 year roadmap of requirements for ocean modelling in the UK.

9. Ocean biogeochemistry

Recommendation 9: The UK ocean biogeochemistry community needs to develop a common model for ESM activity building on the strengths of the existing UK models.

9.1. Ocean biogeochemical models are essential to capture fundamental marine processes that regulate the cycles of key elements and the biogeochemical feedback processes between the land, ocean and atmosphere and their implications for climate.

9.2. The UK aspires to keep its lead in the development of innovative marine biogeochemical models. The UK community has developed a number of different approaches and should now work in close partnership to understand better the role of model complexity in simulating ecosystem processes. It is proposed that one core code should be configured that would be compatible with different biological modules, where the modules could be switched on or off depending on the complexity required.

9.3. The longer term vision is to develop a unified UK community biogeochemical ocean model of appropriate complexity. Building on the common modelling framework the aim would be to use NEMO (or its successor) as a single physical core and develop a single unified ecosystem model which can be configured to give models of different complexity depending on the research question being addressed.

10. Sea floor

Recommendation 10: A sea floor component needs to be developed for the UK ESM.

10.1. The role of sea bed processes is not currently considered in Earth system models. There is a requirement to develop seabed process models of carbon burial, nutrient cycling in shelf seas, methane hydrates and other climatically active gases.

11. Sea ice

Recommendation 11: Development of the sea ice component of ESMs should focus on the CICE model.

11.1. The overall weight of the UK effort in sea-ice modelling should move towards the CICE sea-ice model. This involves transitioning recent improvements in the LIM and CICE sea-ice models to the CICE repository and a better coordination of the UK CICE community.

11.2. A suitable version of the horizontal grid for the CICE model should be developed to assist its coupling to major ocean models, specifically NEMO.

12. Ice sheets

Recommendation 12: GLIMMER-CISM will continue to be the ice sheet model within the UK's strategic ESM. Future developments should build on the existing collaborations with BAS and international partners to enhance the model.

12.1. The UK has a very strong glaciological community which has the ability to maintain and further develop a state-of-the-art ice sheet model within the ESM framework. New developments will see a rapid expansion in the range of problems amenable to ice sheet/ESM modelling over the next five years, making this a component to which more attention will be paid.

12.2. GLIMMER-CISM should be supported in its efforts to be the ice sheet model of choice in the international community. The internationalisation of GLIMMER-CISM will also allow the UK to benefit from the considerable development efforts underway in the US and elsewhere.

12.3. Closer collaboration between the developers of GLIMMER-CISM and BASISM is encouraged, within the context of the JWCRP, to ensure that the next generation of UK ice sheet model benefits from all the expertise and capacity available.

13. Couplers

Recommendation 13: OASIS should be used as the coupler until a new UK ESM framework is developed.

13.1. Current capability is based largely on OASIS (Ocean Atmosphere Sea Ice Soil) coupling software, which is widely used across Europe and beyond (but not in the USA) and provides the basis for interoperability of different model components, through generic interpolation and data passing functions.

13.2. A number of EU funded programmes over recent years (PRISM, METAFOR) have been working towards Europe-wide protocols and systems for Earth System model development.

13.3. In the short and medium term, NERC should engage with the OASIS team and other stakeholders to explore the possibility of developing a more formally managed and resourced development programme.

13.4. The longer term development of couplers will be considered as part of the ESM framework

14. Computationally cheaper versions of the Unified Model: HadCM3 and variants

Recommendation 14: In the short and medium term, a defined set of HadCM3-based models for use on a limited number of platforms should be maintained until such time as a replacement low cost ESM becomes available in the current line of development. User requirements for ongoing maintenance of HadCM3 configurations should be reviewed annually.

14.1. The class of models of various resolutions known as HadCM3 and its variants was developed at the Met Office Hadley Centre in the mid-1990s and remain in very widespread use. At present these models are substantially faster and more memory efficient than current versions of the UK ESM at the same resolution (see section 2). Furthermore, the baseline HadCM3

model is extensively documented and understood. They provide the model of choice for climate impact studies undertaken by non-specialist users and will need to continue to be supported on a limited range of computing platforms.

14.2. The HadCM3 family of models continues to be attractive for new projects, especially those which require long runs or large ensembles. At the same resolution, current HadGEM-based models are considerably more computationally demanding than HadCM3 and therefore at present are not a practical substitute for many purposes. Movement of user demand from HadCM3 to the current model development line would be facilitated by the development of a lower-cost configuration of the current model line (see Section 2).

14.3. The HadCM3 family was implemented in an old version of the Unified Model which is now regarded as obsolete by the Met Office. The large investment of effort needed to port these models to a modern UM version or to the new ESM framework (see Section 3) may be prohibitive. Therefore any further developments of the HadCM3 family of models should be focussed on those that are transferable to the current UK ESM configurations.

15. Earth-System Models of Intermediate Complexity (EMIC)

Recommendation 15: The need to support Earth System Models of Intermediate Complexity (EMICs) should be part of the user requirement for the new ESM framework when this is developed.

15.1. There remains a pressing scientific need to maintain a model capable of long (10 kyr to 100kyr) integrations or fast enough for large ensembles. Such models are needed for understanding the causes of past changes in climate and biogeochemical cycles, but they are also needed for quantifying uncertainty in long term future stabilisation and sea level change scenarios.

15.2. The existing generation of EMICs needs to be maintained and fully documented. However the longer term strategy should be to merge EMICs into the ESM framework to ensure that the components remain at the forefront of EMICs. Integration of EMICs into the ESM framework will allow the assessment of the uncertainty associated with model structure and to allow straightforward application of a spectrum of components to scientific problems.

15.3. This may require development of new fast cores for both the atmosphere and ocean. Such cores are not simply low resolution versions of the high end models, but will require additional approximations to the governing equations. There are considerable challenges to developing and coupling such codes into a universal ESM framework but the benefits could be substantial.

16. Data – Observing systems and palaeodata

Recommendation 16: The development of a new UK ESM framework must be accompanied by concerted action to acquire well calibrated "climate quality" data sets from palaeo records, in-situ and space-based measurements in order to test and to initialise ESMs, and to make these datasets available in a form that can be used by modellers.

16.1. Observations, including palaeodata, are central to ESM. They are required to initialise models, to provide boundary conditions, to improve prediction through data assimilation/nudging, and for benchmarking and testing of models and their components.

There is therefore a requirement for models to have the ability to interface with observations, that appropriate datasets are specified, and that they are then created in a suitable format.

16.2. Specific actions should be taken to include within the ESM framework the flexibility to interface with observational datasets.

16.3. To allow models and observations to be used together, it will be necessary in some cases to develop modules that explicitly predict the variables that are actually measured in both present and palaeo records.

17. Data assimilation and model initialisation

Recommendation: Data assimilation must be developed as an integral component of the UK's strategic ESM.

17.1. Data assimilation must be developed as an integral component of ESM development in order to test the models stringently and to initialise them for climate and environmental prediction.

17.2. There is a need for closer collaboration between the operational and academic communities, and for support and training in advanced data assimilation methods. The JWCRP provides the appropriate framework for collaboration on data assimilation nationally. The 2009 Climate System TAP action on Next Generation Climate and Weather Prediction has one of its two goals as the 'Use of observations to initialise climate predictions'.

17.3. Significant resources will need to be won from national and international research funds in order for the UK to stay internationally competitive in the exploitation of the next generation of satellite observing systems, such as GMES.

18. Data support for ESM output

Recommendation: NERC should consider developing an integrated national modelling output facility within its data centre infrastructure.

18.1. NERC's existing network of data centres, principally BADC, will continue to determine what data should be retained from ESM runs and provide these data to the community. In the longer term NERC should consider developing an integrated national modelling output facility within its data centre infrastructure, where data which have passed the initial analysis phase can be accumulated (from wherever they were generated) to facilitate model-model and model-data comparison.

19. Other issues

Education, training and career development

Recommendation 19: The NERC centres should develop a career structure for Earth System modellers who are critical to the delivery of NERC's strategy but are undervalued using the usual academic metrics for career advancement such as publication rate.

19.1. UK leadership in ESM will depend on the ability to develop and motivate the next generation of young scientists whose skills couple computational and natural sciences.

19.2. Within a broad spectrum of individuals we will need both those who can harness ESMs efficiently to address the science, and those who can build and deploy efficient codes which can exploit a rapidly changing computational landscape. To that end, the UK needs to develop a coherent approach to ensuring the right training and career structures are in place. A particular issue is to provide a career structure for those highly-productive scientists specialising in model and code development, who might not be considered productive by standard academic metrics such as publication rate.

19.3. NERC is conducting a postgraduate skills review on behalf of the Environment Research Funders Forum. Early results from the consultation "*suggest that over the next decade there will be a growing need for competent modellers to address the challenges facing the environmental sciences sector. These people will need to be numerate, able to manage large amounts of data and have the capacity to work across a range of complex systems*".

High performance, grid and cloud computing

Recommendation 20: NERC should continue to support and develop its computing platforms in partnership with others to provide access to both more powerful High Perfomance Computers and also other distributed computing architectures.

19.4. Increased investment in HPC infrastructure is necessary if the UK is to remain internationally competitive in ESM. In the next decade, computational capability is expected to increase in the number of processors rather than in individual processor power, with massively parallel supercomputers expected. The HPC roadmap to address this challenge will be finalised by NERC in the coming months.

19.5. It will be a major challenge to exploit this next generation hardware. For example, as discussed above, the 'dynamical cores' of climate and weather models that have been developed on today's computers, will not be able to exploit the available processing power. An important step is NERC and the Met Office partnering with the STFC Hartree Centre to research, design, and develop a new atmospheric dynamical core for the Unified Model to enable the UM to exploit next generation hardware (see paragraph 4.2).

19.6. ESM development also needs to take account of ongoing developments in Grid and Cloud computing. This represents an efficient alternative to HPC for experiments such as the large ensembles necessary for risk analysis and the compilation of extreme event statistics. ESM developments need to develop a traceable hierarchy of models between the highest-resolution, highest-complexity models that can only be run on multi-thousand-processor HPCs, and lower-cost models that can be run on Grid or other distributed architectures.