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NERC

NERC Strategy for Earth System Modelling

Annexes 1 to 3

Version 1.1

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Annex 1

NERC Strategy for Earth System Modelling – Extended Version

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 Introduction

This Earth System Modelling Strategy has been commissioned by NERC and written by a team of experts, the ESM Strategy Group (see Annex 2), supported by Assimila Limited. The document presented here for consultation has been drafted following two meetings of the Strategy Group. The Terms of Reference for the Group are presented in Annex 3. A national audit of the UK‟s Earth System Modelling capabilities, benchmarked internationally and assessed against NERC‟s strategic requirements was compiled by Assimila and used as an evidence base by the ESM Strategy Group[1].

The aim of the activity is to develop NERC‟s 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.

Earth System Modelling is a dynamic developing discipline. The Strategy will provide a framework for identifying and selecting the ESM activities that will be supported by NERC in the context of both National Capability and Research Programme activities, particularly those activities which require sustained support as part of NERC‟s National Capability portfolio. 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.

1.2 Motivation for an ESM Strategy

A key goal of NERC‟s strategy is to develop improved environmental prediction on timescales of days to decades. At the shorter timescales these predictions will form part of the proposed UK climate service to a wide range of public and private sector organisations. At the longer timescales they are critical to the formation of evidence-based policy on climate change mitigation and adaptation, and geoengineering. 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 to maintain UK 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. This demands an over-arching strategy that is visible and widely understood in the community.

The predictions of future trajectories of CO_2, and other greenhouse gases (GHGs), require the simulation of the dynamic interactions between the atmosphere, the land surface and oceans. It is also necessary to represent the complex chemical reactions within the atmosphere which are precursors to the GHGs themselves. Thus any future prediction of climate change (or simulation of past changes) requires the use of a fully coupled Earth System Model – containing an adequate representation of atmospheric chemistry, the land surface and ocean biogeochemistry as well as atmospheric and ocean dynamics.

The prediction of possible future climate requires estimates of future emissions (of GHGs) and land use changes (including agricultural change). These possible futures will be largely controlled by political, social

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[1] *"NERC Strategy for Earth System Modelling: Technical Support Audit Report",* Version 1.1, Assimila Limited, December 2009

and economic drivers outside the scope of current ESMs used by the NERC community and Met Office. Models for these components (and interfaces between them and the physical components) are not sufficiently well developed to be included in the generation of ESMs envisaged within this strategy. In future strategies these may be included.

The outputs of ESMs are of vital importance to an increasingly diverse set of users. There is an urgent need for more confident and accurate predictions of the future state of the environment so that society can make the informed decisions that will be necessary if it to be able to respond to a changing environment.

ESMs and their components are highly complex pieces of software requiring many person years to develop and maintain. NERC supports a wide range of ESM related activities, yet until now, NERC has not tried to develop an overall strategic framework for the long term support and development of these models.

1.3 Scope of the ESM Strategy

A joint action from the Climate System and Earth System Science Theme Action Plans to develop and implement a NERC contribution to a National Strategy for Earth System Modelling (ESM) was approved by NERC Council in 2008 to provide a strategic framework for the long-term support and development of these highly complex models, to secure existing capability, ensure effective coordination of activities at a national level, and embrace new developments.

NERC Council specified that the national audit of ESM capabilities has three parts covering major tools for modelling: a) physical climate system (to include modelling infrastructure); b) biological and chemical feedbacks on climate; c) climate impacts. NERC Council requested that parts a) and b) should be conducted first, and the focus for these parts should be on global models, or components thereof. This is the subject of this Strategy. There are therefore other important areas that are not part of this document, e.g. climate impacts, local/regional models, weather forecasting, socio-economic modelling, Earth core/plate tectonics and the mesosphere. Some of these have interfaces with the models that are being considered here, but they are not at the heart of this strategy.

Historically, in the UK, the Met Office Hadley Centre (MOHC) has led the effort to develop weather forecasting and climate models and now works in partnership with NERC in the development of full Earth System Models. NERC‟s involvement has increased steadily over recent years, to the extent that NERC has been the leader of major collaborative modelling projects such as HiGEM (focussing on high resolution climate modelling), and QESM (developing a new Earth System Model), and has a central role in several projects to develop components of Earth System Models (e.g. JULES, UKCA, NEMO). The Joint Weather and Climate Research Programme (JWCRP) is an opportunity to forge a stronger partnership between NERC and the Met Office in Earth System Modelling and its applications.

Equally, it is important to emphasise that NERC‟s interests in Earth System Modelling are not limited to collaboration with the Met Office. GENIE and ICOM are examples of NERC funded ESM activities in which the Met Office is not (currently) involved.

Many of NERC‟s ESM activities are being developed within Research and Collaborative Centres (e.g. JULES at CEH, UKCA at NCAS, NEMO at the Marine Centres), and there is ongoing commitment from these centres to support these activities as National Capability. However, in recent years NERC has also supported a number of new ESM activities through time-limited consortium funding (specifically: HiGEM, UJCC, GENIE, QESM, ICOM). The Theme Action Plan identified that that there was a danger that the models and expertise would be lost before a strategic assessment had been made. Limited interim funding was therefore made available until March 2011 to ensure that key expertise associated with these projects is not lost, and that these ESMs can be maintained and supported for community use, while completion and implementation of the NERC Strategy for ESM takes place.

1.4 Strategic Objectives and Future Direction

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.

In this document, specific ESM configurations are considered to be composed of component sub-models (atmosphere, land surface, ocean etc). Separate strategies are proposed for each component sub-model, reflecting the different communities and issues surrounding each (Sections 0-12). In addition, a strategy for developing the ESM configurations themselves is proposed in Section 2. Finally, the development of these ESM configurations must be underpinned by a software framework to allow easy coupling of the sub-models and running of model experiments; this is described in Section 0.

Over the coming years, as Earth System Models become more complex and the scientific questions asked of them become more challenging, it will become increasingly important to entrain large and distributed communities of scientists in their development. In this new environment, ease of use will become particularly important for those wishing to carry of scientific experiments or address policy questions. A software framework will be required that facilitates both „research‟ use, requiring ease of use and experimental setup, and a level of interoperability of alternative model components, and „operational‟ use, where the requirements focus on code stability and management, and computational efficiency.

Scientific requirements will include:

- A small set of „baseline‟ models that provide an adequate simulation of present-day climate and recent climate change. Scientific content of the baseline models should be traceable to that of „operational‟ models used for weather, climate and marine prediction, so that new scientific insights can quickly be pulled through into operations.
- Ability to interface with a high resolution regional modelling capability for climate impact studies (although the regional models themselves are not considered by this Strategy).
- Ability to interface with state-of-the-art data assimilation and ensemble generation systems to initialise predictions (Section 17).

Technical requirements include:

- Sufficient flexibility to address key scientific challenges, including an open model-development environment.
- Ease of use for „entry level‟, non-specialist users, making the ESM tools attractive to researchers.
- Transparent, flexible input/output, compliant with international standards.
- Support for a variety of computing platforms, including grid implementations for ensembles.
- Computational efficiency, particularly on massively parallel architectures.
- Simple and investigator-friendly licensing terms.
- A governance structure and associated IT infrastructure that allows investigators easy access to up-to-date model versions, and a pathway back from research into the development of operational models.

All of these points will need to be addressed if the UK-branded ESM family is to remain an internationally competitive Earth system modelling structure.

1.5 International Dimension

The ESM Strategy confirms NERC‟s main objective is to work with MOHC to continue to develop a UK branded Earth System Model. However, this cannot be achieved in isolation and without reference to the international community. The current HadGEM family of models already includes major components (physical ocean: NEMO and sea ice: CICE) initially developed overseas which require ongoing international collaboration. The EC‟s Framework programme provides significant funding for working with colleagues in non-UK institutions and this funding stream should be exploited by the UK, including encouragement to lead major projects where appropriate. UK will also continue to take an active and leading role in international intercomparison experiments (eg CMIP5 currently under way as input to IPCC AR5). UK scientists have also developed a wide range of close bilateral collaboration, notably with France on NEMO and with the US and Japan. Further international collaboration should be encouraged and facilitated by NERC, particularly where this collaboration helps to promote UK capabilities and UK derived model components (recent examples include the development of NUGEM as part of the UK Japan Climate Collaboration, a collaboration with Japanese scientists based at the Earth Simulator in Yokohama; and the emergence of GLIMMER as a prominent ice sheet model in the international community) or where UK needs influence on international developments (eg NEMO).

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 Current Capability

HadGEM2-ES is the latest generation ESM in the HadGEM family, and this will form the bulk of the UK‟s submissions to the CMIP-5 database for use in the IPCC 5th Assessment report. While this includes a wide range of „Earth system‟ processes and feedbacks, the model physics is however a „dead end‟, in that the old UM ocean and sea ice models are used. Future developments will be based on the HadGEM3 family, which uses NEMO ocean and CICE sea ice models. Currently only atmosphere-ocean („-AO‟) versions of HadGEM3 are under development, at two primary resolutions, N96/1° and N216/0.25°. The N96 version is in use operationally for seasonal forecasting. This may transition to N216 during 2011, if computing resources allow. A HadGEM3-ES model version is planned around 2013-2015.

The HiGEM model is based on the HadGEM1 model used in CMIP3/IPCC AR4, but explores the effects of higher resolution (N144/0.33° as opposed to N96/1°). A small number of initialised decadal predictions are expected to be submitted to CMIP5 using this model.

The QESM model is a low resolution version of HadGEM3 (N48/2°) which allows the development and use of a range of ES components and the exploration of longer timescales than would be possible at the standard HadGEM3 resolutions..Its low resolution makes it an attractive tool for addressing scientific questions that are not accessible using the standard HadGEM configurations.

Figure 2-1 shows the current HadGEM model family, positioned in complexity/resolution space. These models have been configured with a view to delivering operational requirements on supercomputing capability that can be foreseen in the next few years. The current HiGEM and QESM projects can be viewed as exploratory activities which extend these models in resolution or complexity, and so are prototypes for the operational models of the future.

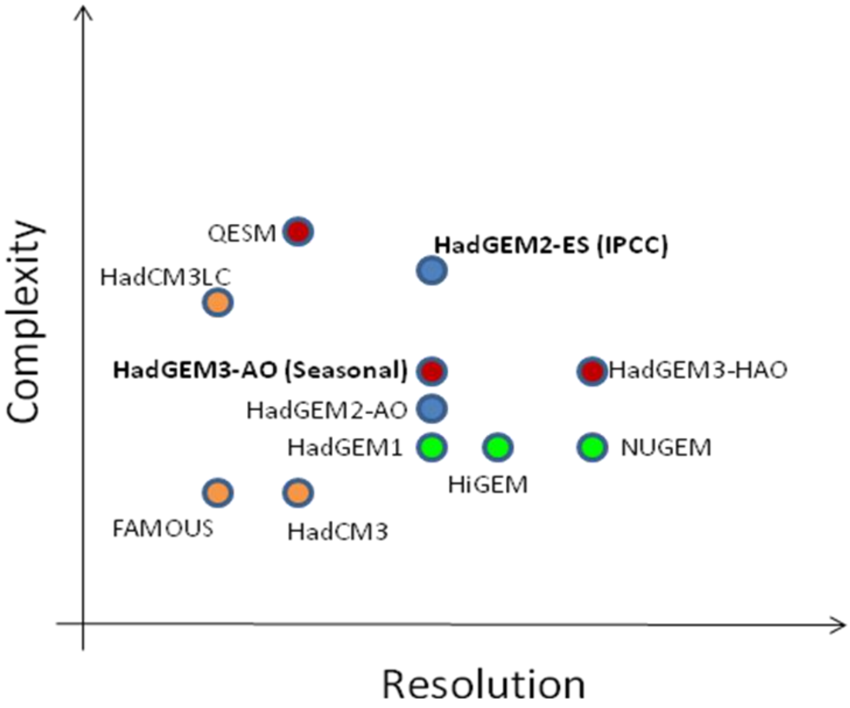

Figure 2-1: Schematic of the current HadGEM model family, showing variations in resolution and complexity. Increasing complexity or resolution generally implies increasing computational cost. Models currently used quasi-operationally are shown in bold. Groups of models with approximately traceable physical formulations are indicated by common colours (essentially the HadGEM1, HadGEM2 and HadGEM3 families). However note that in practice it is difficult for these projects to maintain traceability to current versions of the operational models. The older HadCM3 model family is still widely used (see Section 14), and some common versions of this family are also shown (FAMOUS refers to a low-resolution atmosphere-ocean configuration of HadCM3).

2.2 Issues/Requirements

Development of Earth System Models needs to proceed along two axes, namely increasing resolution and increasing complexity (both in the range of Earth System processes represented and in the sophistication of those representations). Moving along each of these axes implies an increase in computational cost. Meanwhile there is an ongoing requirement to run cheaper models (at lower resolution or complexity) to address specific scientific questions or to allow large ensembles to be run. (Also see discussion in Section 14 on HadCM3 and variants and Section 15 on Earth System Models of Intermediate Complexity).

2.3 International Context

A number of international initiatives address the development of Earth System Models. For example, in the US a multi-agency programme on „Decadal and regional climate prediction using Earth system models‟ is making available US$45-50M for its first proposal round, while the EU supports a number of related research programmes through its FP7. The UK is a leading international player in this field, and can continue to be so provided it exploits fully the cohesiveness of its science community, and engages with and participates in international programmes where appropriate.

2.4 Strategy

The proposed ESM development strategy is illustrated in Figure 2-2. At any point it is envisaged that there will be a need for several „operational‟ ESM configurations. These will need to balance scientific complexity and resolution against the available computer time for their applications – for example seasonal to decadal prediction (with a possible need for high resolution to obtain good representation of regional modes of variability, and a need for large ensemble size to span initial condition uncertainty), and centennial climate prediction (with a need to run for longer timescales, possibly with ensembles spanning model physics uncertainty).

For the foreseeable future, there will be a need to explore both increases in resolution and complexity, beyond what is possible in current operational configurations, and more sophisticated experimental designs. Therefore, both high resolution configurations and low computational cost configurations (reduced resolution, reduced complexity or both) should be maintained so that they are traceable to specific HadGEM standard configurations. The maintenance of a low cost version traceable to an operational configuration allows for easy testing of ES component changes in coupled mode and enables pull through into operations, as well as acting as an important tool for exploring scientific questions not accessible to the operational configurations due to computing cost: examples include perturbed physics ensembles, paleo-climate simulations and coupled data assimilation that are currently only achievable with the HadCM3 family (Section 14). It is not expected that new high resolution or low cost versions would be produced parallel to each prototype version of the operational models. The development of the high resolution and low cost versions would be a logical extension of the work of the current HiGEM and QESM teams, and subject to broader negotiation with key partners in the strategy.

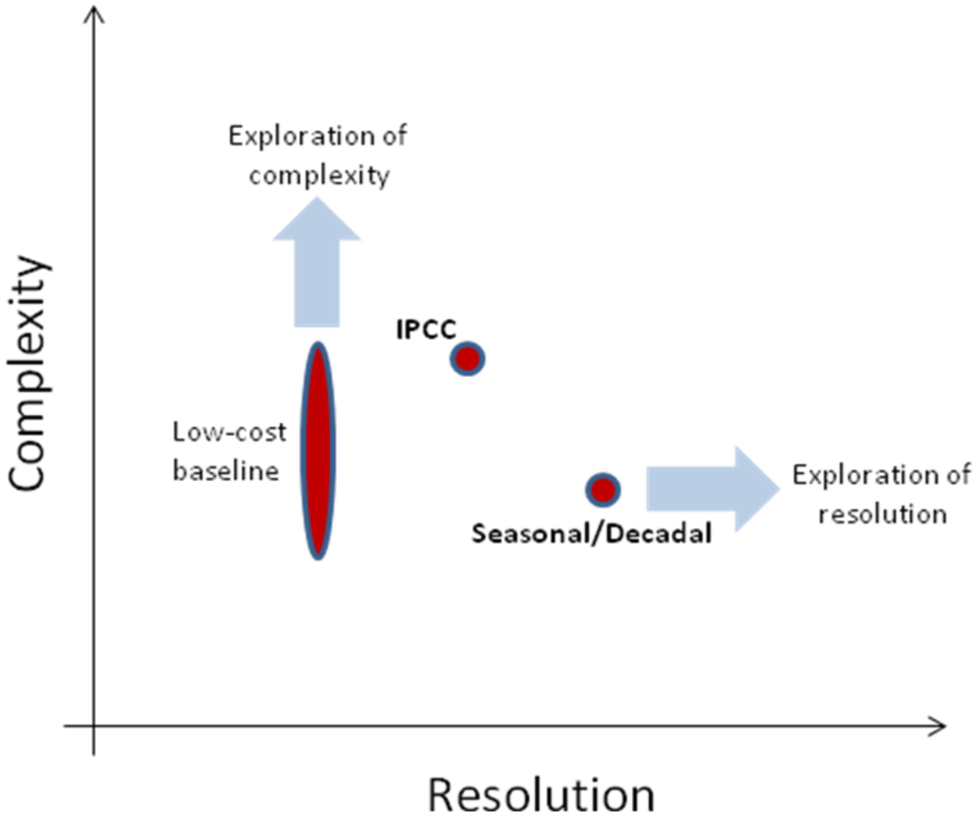

Figure 2-2: The proposed ESM development strategy. Developments are maintained in a way that is traceable to standard operational configurations (in this case IPCC and Seasonal/Decadal configurations are shown as the operational versions). The baseline low-cost configuration is both a 'workhorse' model for science that is too computationally expensive for the operational models, and a testbed for evaluating new component models in an ESM context. It is shown here as spanning a range of complexity, since some aspects of its formulation may need to be modified to deliver the required runtime performance. In general it is expected that the seasonal-decadal configuration will evolve more frequently than the other configurations. It is not expected that every seasonal-decadal configuration will maintain widely-used counterparts in the other configurations. Exploratory work is linked to increasing resolution and/or complexity, with the expectation that the operational configurations will exploit the exploratory work to move towards the top right of the figure, as computing resources allow. New developments are tested as soon as possible in the most up to date baseline model, to facilitate pull through to operational use.

2.5 Implementation Pathway

There is an early need to agree the overall development strategy with the Met Office and other key partners. This is an urgent requirement since if NERC is to play an active role in the development of coupled ESM configurations (e.g. the low and high resolution configurations), there is a need to maintain robustly NERC-funded core teams in these areas (currently supported through time-limited funding to QESM and HiGEM teams, ending September 2010/March 2011). The role of these core teams would be:

- Develop, evaluate and maintain core low and high resolution ESM configurations based on (traceable to) standard operational configurations
- Perform baseline integrations, and evaluate these against a range of metrics
- Use process-based diagnostics to address specific high priority model biases/weaknesses, in collaboration with specialist component model teams.
- Work with specialist communities to implement and evaluate new sub-model developments in ESMs
- Make model configurations and baseline integrations available to the wider community.
- Maintain a limited number of earlier model configurations on a limited number of platforms, where there is a clear requirement to do so in order to deliver NERC strategy (e.g. HadCM3 family, Section 14). Responsibility for maintaining earlier configurations that do not fall into this category will rest with individual programmes/projects.

These activities would be carried out in close collaboration with the Met Office and other partners in ESM, and methods of management and decision making would need to be agreed. The governance agreement would need to recognise the need for operational agencies to maintain an appropriate level of control over the „operational" configurations, although with significant input and collaboration from the core teams and the wider NERC community. It would also need to recognise appropriately the intellectual input from outside the operational agencies in ESM development. The governance structure would also need to encourage easy research use, and provide a simple and efficient pathway for developments in the research domain to feed back into improved operational versions. *This needs to be backed up by a community IT environment that supports these requirements.*

The requirement to run configurations at higher-than-operational resolution, and lower-than-operational cost (possibly including both lower resolution and lower complexity), needs to be built into the design criteria for each of the component submodels.

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 Current Capability

In the context of Earth System Models, frameworks are sets of rules which define in precise terms how the numerous components within models must communicate with each other, and which provide an environment for setting up and managing model runs for operational and research use. The principal advantages are that components can be developed separately, components of different models can be exchanged and that models may more efficiently handle multiple alternative options for physical components. In the UK, much of this capability for the HadGEM model family is provided by the Met Office Unified Model (UM) system and the OASIS coupler (Section 13); the UM system allows a wide range of flexibility in the configuration of model runs through the UM User Interface (UMUI), including extremely flexible definition of output options and job control. However, much of the UM system code is intimately linked to the data structures of the Met Office atmospheric model, meaning that introduction of new code can sometimes require quite complex programming over multiple code levels.

3.2 Issues/Requirements

The UK needs a model framework for Earth System Models that meets or enables the following requirements:

Configurability. The framework must facilitate multi-model configurations (for example, climate configurations and weather forecasting configurations) and multiple options for individual processes. For research purposes, it must be easily possible for users to understand and modify the model code.

Flexibility. It must be straightforward to import and export model components to and from other models sharing the same framework, enabling and encouraging international collaboration, particularly on the development of model process components. Since other international frameworks are implemented within an open source licensing model, it is desirable that this approach should be explored.

Performance portability. The framework must use established software standards making implementation on a variety of computer hardware readily achievable. This must be achieved while keeping the execution time and costs associated with the framework itself to an acceptable level. Trade-offs will need to be considered recognising potentially conflicting needs between the Met Office, which has a need to maintain operation configurations that must run very efficiently and robustly within this framework, and for whom portability is not so important and the research community for whom portability is highly desirable.

Documentation. The framework itself must be rigorously and unambiguously documented and should also include a substantial capability for self-documentation of individual model setups.

At the same time, the model code and framework code need to be maintained in a manner which both allows and exploits distributed development and delivers scientific provenance of the model configurations.

Effective code management. The framework must facilitate efficient code management by allowing model components to be straightforwardly transferred to new versions of the model or to different combinations of components. The framework must enable traceability of model evolution through successive versions.

3.3 International Context

Internationally, two significant frameworks are the Earth System Modelling Framework (ESMF) and the Project for Integrated Earth System Modelling (PRISM). The design concepts of ESMF and PRISM are different and are not discussed in detail here. ESMF is more comprehensive in its ambitions and components are often nested within each other; it addresses climate and weather models and also data assimilation. PRISM allows direct communication between components but has been thus far focused primarily on climate models. A significant number of US climate and weather prediction models (including the GISS model, CCSM and the NCEP weather forecasting model) use ESMF in some way. The principal achievement of PRISM is the provision of the air-sea coupler (OASIS) for several models including the Met Office Unified Model (UM) model. While there is some international momentum behind the development of these modelling frameworks, wide convergence and buy in to an agreed framework has not been achieved yet.

Some progress towards developing a framework for the UM has been made in the Flexible Unified Model (FLUME) project but FLUME implementation is currently immature. Within the UK, the Bespoke Framework Generator (BFG) provides both inspiration for the FLUME project and a more mature implementation that, in some deployments, provides faster coupling than the larger international efforts.

3.4 Strategy

Development of a framework that meets all the requirements above is a major software engineering task.

Given the ongoing need to deliver operational climate predictions on all timescales, an evolutionary approach is most likely required. An early deliverable will be to establish and implement a plan to deliver interim improved usability of the UM system, including a clearer separation between its atmosphere model and its control framework, and sharing of latest ESM development versions, over the short to medium term. This is required to enable the wider scientific community to engage with the longer term strategy and deliver some of the benefits of the full system at an early stage.

Precise long term goals and priorities, governance and ownership of the framework need to be established at an early stage through discussion between NERC, the Met Office, and other stakeholders. It is expected that this will lead to a joint set of agreed requirements that can guide an implementation project.

3.5 Implementation Pathway

A workshop will be held at an early stage to identify needs and opportunities for interim work to facilitate use of the UM in the research community, including up to date versions of the HadGEM model family. This will inform discussions between NERC, the Met Office and other UM partners on a possible project to deliver these improvements over a timescale of around 2-3 years.

Longer term development of the ESM framework is likely to require input from a wider set of partners. For example, international UM partners, EPSRC and STFC will be consulted. The first task will be detailed design of the requirements and implementation approach. A beginning Met Office/NERC/STFC project to design and implement a new atmospheric dynamical core provides an opportunity to redesign the UM atmosphere model, possibly achieving greater separation of control code from science code. The work of the framework and dynamical core teams will need to be carefully coordinated to achieve this.

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 Current Capability

Within the NERC research community, the most frequently used atmospheric model is the Met Office Unified Model in many different forms, used for both climate and weather applications. The Unified Model is now a non-hydrostatic model (since the adoption of the "new dynamics" several years ago) although there is still some use of the older HadCM3 model (which is hydrostatic), particularly for paleo-climate work. The progress towards higher resolution mean that the non-hydrostatic capability is increasingly essential for most applications. The UM uses a staggered grid which in the latest versions has some stretching capability in the horizontal. Two features allow the UM to take very large time-steps: the use of a Helmholtz equation to determine the pressure and a semi-Lagrangian advection scheme. To date these features have been ideal for computational efficiency. This is especially important in operational weather forecasting. Difficulties with this approach are that the semi-Lagrangian advection scheme does not conserve mass and that whilst the Helmholtz equation approach was efficient on previous supercomputers with vector processors, it is difficult to parallelise for the next generation of massively parallel systems. Current work at the Met Office will implement a mass-conserving version of the semi-Lagrangian scheme operationally within the next few years. Lack of mass conservation is unimportant for most weather applications but is increasingly presenting problems for long, high resolution climate runs. The UM is sometimes run operationally with a fine grid nested within (and forced by) a coarser grid. For example, a north Atlantic and European domain is nested within a global domain. The UM does not have the capability to feed information back from finer grids to coarser grids (i.e. It has a one-way nesting capability). Several countries licence the UM from the Met Office for operational forecasting use and this increases the user base and community of developers.

The weather research community makes increasing use of the Weather Research and Forecasting (WRF) model. This model is developed and maintained by the National Center for Atmospheric Research (NCAR) is the USA. This is an open source, modular modelling system using rather newer software approaches than the UM. It has a very large worldwide user base and is used by operational weather services in many countries. WRF uses the fully compressible equations of motion which removes the need to solve a Helmholtz equation but requires the use of small time steps. A high order, conservative advection scheme is used on a staggered, uniform grid. Scalability on massively parallel computer systems is generally good (thousands of processors are often used effectively) but this is still insufficient for the expected needs for ~10^5 processors in the near future. WRF has many options (and as a consequence is less well tested and tuned than the UM). It is relatively easy to use and to adapt the code; this is largely responsible for the widespread research usage. WRF is essentially a limited area model, although a global version has now been released. The WRF is a powerful tool for very high resolution work as a result of its two-way nesting capability. Frequently up to four levels of nesting are used, allowing very high resolution in limited inner domains.

There is a small but growing community in the UK using the NCAR Community Climate System Model (CCSM). Like WRF, this model is open source, modular and relatively easy to use. The current scalability of CCSM is similar to that of WRF.

There remains an important role for simpler models, particularly for testing new application ideas in atmospheric dynamics. Because of its ease of use, the WRF model plays this role, in cut down form, for the weather modelling community. For the climate modelling community the principal simple tool is the Intermediate Global Circulation Model (IGCM).

There are small but active projects aimed principally at developing new atmospheric dynamics techniques. AtmosFOAM is a new dynamical core being developed within NCAS, with a view to implementing adaptive mesh techniques. VHREM is another simplified model development within NCAS which implements a terrain-intersecting grid.

4.2 Issues

The principal issue for future atmospheric dynamics developments will be the need to exploit massively parallel computer architectures in order to achieve the very high resolutions required in the next 5-10 years. It is expected that on this time-scale single climate or weather model runs will need to exploit over 10^5 cores efficiently. Current codes scale poorly for such large numbers of cores and so novel parallel algorithms will need to be developed.

For long climate simulations and particularly with applications involving chemical transport or aerosols, it is important that advection schemes are conservative. Thus any development in parallel scalability should go along with ensuring appropriate conservation properties.

Many future applications will require a regional or local focus in which additional resolution can be achieved in specified regions of interest. Current this capability can only be achieved by the one-way nesting capability of the UM, the limited grid stretching capability of the UM, or the two-way nested capability of the WRF model. In the future, more flexible approaches will be needed which do not have the dispersion and reflection problems associated with abrupt changes in resolution or mesh structure. This will involve some form of smooth stretching without nesting and probably, for global applications, a fundamental restructuring of current rectangular grid structures.

In the more distant future, it is likely that fully unstructured and adaptive grid approaches will be developed. For atmospheric applications, the greatest challenges associated with these developments are likely to concern the representation of complex physical processes (e.g. turbulence, cloud micro-physics) on varying grids. For these reasons the emphasis for the next 5 years should be on semi-unstructured and fixed grids, moving to fully adaptive grids on the 10-15 year time-scale.

4.3 International Context

The UK is a leading international player in atmospheric dynamics, and can continue to be so especially if, through collaboration, there is extensive use of experience gained by the teams developing WRF, CCSM and next generation NCAR model MPAS (Model for Prediction Across Scales). Collaboration with Deutsche Wetterdienst is also likely to be valuable, as similar model development issues are being addressed there.

4.4 Strategy

The imperative (because of parallel scalability issues) to develop a new dynamical core and code structure in order to exploit the emerging super-computer technologies suggests that little or no further development of the existing UM should be undertaken within the NERC community. There will by necessity be some further development by the Met Office for operational reasons. The entire emphasis of the NERC community in its usage of the UM should be directed towards science exploitation of the existing capability. Particular attention should be devoted to developing a more detailed science strategy in this area.

The WRF model has a more modern structure but even this will be replaced on the time-scale of 5-10 years. The next generation NCAR model MPAS (Model for Prediction Across Scales) is already approaching the stage of testing a new grid and dynamical core. Developments within WRF should be restricted to its use as a test-bed for new computational methods and physical process representations, with the majority of the effort being devoted to science exploitation of the existing capability. Particular attention should be devoted to developing a more detailed science strategy in this area.

There is likely to be a continued but low level requirement for simple models such as the IGCM. The current low level of support for such activities should be continued. There will also be continued but unsupported usage of other models such as the CCSM.

The primary model development activity should be directed to developing and testing the next dynamical core for research usage within the Met Office and NERC communities and for operational Met Office usage. NERC can take a lead in this, working closely with the Met Office. The implementation of a new dynamical core must be done within a new model framework, which takes account of:

- the requirement for an internationally recognised and well-documented model framework, which will allow exchange of code with other groups internationally and between model versions;

- the requirement for the adoption of modern software development practices, including up to date version control and the adoption of a "trunk and branch" approach to simultaneous maintenance of a core model whilst encouraging widespread experimentation with new techniques;
- the necessity for a NERC community research model to allow many model options.

The "trunk and branch" approach is essential for the encouragement of innovative development, in which many individuals or groups experiment with new model capabilities (branches) coming from a common core model (trunk). However, the NERC community will need to accept that adoption of branches into the next version trunk will have to be largely under the control of the Met Office (because of the operational requirement).

There will need to be a continued, sustained but relatively low level effort directed towards fully adaptive dynamical cores which will be needed in the more distant future. Therefore activities such as the AtmosFOAM project should continue.

4.5 Interfaces

In parallel with the development of the new core, it is essential that an activity prepares the way for the adoption of an up to date and internationally recognised model framework (see Section 3).

4.6 Implementation Pathway

NERC has already committed, through the most recent climate theme action plan, 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. It is reasonable to expect testing of a new core model and framework in three years, especially if experience from international collaboration fully exploited.

Following the development of a new dynamical core, it is important that maximum usage is made of the existing process modelling and understanding implemented within the current UM. There will therefore need to be a major porting effort to bring the existing knowledge into the new model. The additional grid flexibility which will be built into the new model will require considerable additional work in adapting physical parametrisations (see Section 5).

In parallel with the implementation of physical process modelling, there will need to be a major development effort to implement the current UM 4-D variational data assimilation capability into the new model.

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 Current Capability

The way that sub-grid-scale physical processes are parametrised has a major impact on the simulation of atmospheric dynamics. Such parametrisations include the diabatic heating through radiative transfer in the atmosphere, convective processes in the atmosphere including phase changes involving water vapour and the development of clouds, the treatment of the planetary boundary layer and the representation of gravity waves.

The currently available atmospheric models used by the NERC community and including comprehensive physics modules are:

- the Unified Model in various NWP and climate modes;
- the WRF model;
- the CCSM model.

The audit includes summaries of the capabilities and it is inappropriate to repeat here, both because the range is vast and because the priorities should be for establishing the infrastructure within which the sub-model of physical processes can be developed and expanded.

Broadly, the range of processes includes:

- sub-grid-scale turbulence;
- sub-grid-scale convection;
- gravity-wave drag;
- boundary-layer and surface layer representation;
- clouds (liquid and ice phases);
- radiation (both long-wave and short-wave);
- aerosols;
- precipitation;
- land-air and ocean-air exchanges.

This section does not discuss chemistry modules, which are dealt with elsewhere.

5.2 Issues

Much of the current research in the NERC community is aimed at improving fundamental understanding of physical processes and their representation in models. The current UM is designed for operational efficiency and it difficult for researchers to use as a test-bed for process studies, including model development. WRF and CCSM are easier in this respect because they are built in a modular way with the expectation of numerous options for physical process representations. The forward strategy needs to encourage process experimentation.

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

- the development of explicitly resolving models (e.g. appropriate numerical schemes which permit explicit prediction of convection or gravity waves);
- the co-existence of resolved and sub-grid-scale representations of the same processes when resolution is insufficient for complete resolution;
- the seamless transition of schemes from parametrised to resolved as resolution increases.

It is largely because the third of these is so challenging that fully adaptive grids are a much more distant prospect for atmospheric models than they are for ocean models.

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.

It is highly likely that current research-grade observations are insufficient for complete validation of new process representations.

5.3 International Context

As noted in previous sections, atmospheric modelling is a key strength in the UK science community and can continue to be so, provided strategic international partnerships are developed to make extensive use of experience gained within international teams. NERC scientists‟ main interfaces at present, on the international stage, are with NCAR.

5.4 Strategy

The challenge for the Earth System Modelling strategy is to ensure a sufficiently flexible framework to allow active process research leading rapidly through to development and testing of model representations of processes.

5.5 Interfaces

The essential part of the ESM strategy for development and implementation of atmospheric physical processes is in the design and flexibility of the underlying model framework (see Section 3). This requirement needs to be at the core of the framework design.

Atmospheric physics parametrisations 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 massively parallel dynamical cores (Section 4).

5.6 Implementation pathway

NERC has already started to implement a strategy in discipline-based process research, which should continue to support the already strong capabilities of the NERC community in this area. The need for research-grade observations will need to be addressed through other parts of the NERC National Capability strategy (future NCAPs) and Theme Action Plans.

The development of new parametrisations and process representations will need to take place through future theme actions.

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 Current Capability

The concentrations of trace gases and aerosols in the atmosphere, including greenhouse gases, are affected by emission and deposition at the surface, transport by the atmospheric circulation (advection, convection, mixing), and in-situ chemical or physical processes. To represent atmospheric pollution in ESMs, as well as the two-way coupling between the climate change and atmospheric composition (chemistry and aerosols), equations representing the simultaneous evolution of many trace gases must be included in ESMs.

Inclusion of chemistry and aerosols in a 3D model requires (i) a module to calculate the chemical reactions and/or aerosol processes in each model grid box and (ii) a coupling with the model transport schemes and physical parameterisations (e.g. surface deposition or washout). The aerosol/chemical modules can, in principle, be coupled to any model framework for development purposes or for different scientific studies. The three general classes of 3D models available are fully coupled (e.g. ESMs), "nudged" models and off-line chemical transport models (CTMs).

The UK Chemistry and Aerosol model (UKCA), is a module of the MOHC Unified Model developed jointly by scientists at the NERC National Centre for Atmospheric Science and the Hadley Centre

(http://www.ukca.ac.uk/wiki/index.php/Main_Page)
This is a major new tool now available for the UK atmospheric community (and for international collaboration) providing advanced atmospheric chemistry and aerosol components for chemistry-climate studies. UK Universities in NCAS, mainly Cambridge (chemistry) and Leeds (aerosol) have led the development of the new schemes. A range of chemistry schemes is available, including tropospheric (Ox, NOx, HOx, methane and a range of natural and anthropogenic VOCs), stratospheric (Ox, NOx, HOx, ClOx, BrOx, etc.) and whole-atmosphere (see e.g. Morgenstern et al., 2008a, b, O‟Connor et al, 2009), based on earlier extensive work using the off-line CTMs, TOMCAT and SLIMCAT. The new whole-atmosphere scheme, combining a comprehensive ozone chemistry in the stratosphere and fairly detailed tropospheric oxidation chemistry, including the major VOCs of importance to the free troposphere, is currently being tested off-line; the other schemes are already being exploited in scientific studies. The complexity of the current schemes makes them well suited to centennial scale investigations. Detailed schemes for a wide range of aerosol types have been developed and tested off-line and are now implemented in the model (Mann et al., 2009). In UKCA the particles are now defined by the microphysics with both number and mass as prognostic variables. In contrast to CLASSIC (the scheme used in earlier versions of the UM), this allows realistic predictions of variable particle sizes and number concentrations as observed through the atmosphere. The aerosol is coupled to the chemistry and allows for mixed composition particles, enabling cloud condensation nuclei to be quantified. UKCA aerosol is coupled to a model of cloud drop number concentrations, allowing the cloud indirect forcing to be calculated mechanistically. The same aerosol scheme is available in a CTM (TOMCAT), the UM, QESM, and the ECMWF Integrated Forecasting System (from 2011).

Biogenic emissions will use the MEGAN scheme (Guenther et al., 2006, also see Section 7) while surface deposition can be calculated interactively, depending on surface type.

There is also a "nudged" version of the model (Telford et al, 2009), in which dynamical fields are relaxed back to analyses. (So, the „nudged‟ model behaves like a CTM but has the advantage that all model sub-components are identical to those included in the free-running UM.) Like a CTM, the nudged model ensures that the model meteorology remains close to observations. The nudged model is a powerful tool for model evaluation studies, for investigating the role of particular processes, or for investigating particular periods in detail.

UKCA is one of the key components of QESM, the community model being developed by UK scientists (see Section 2). UKCA provides the chemistry and aerosol schemes. Interactive chemistry and aerosols (GLOMAP-mode) in UKCA are coupled to the terrestrial and oceanic precursor emissions (from JULES/MEGAN and PlankTOM10, see Sections 7 and 9), thereby interactively influencing atmospheric composition and aerosol. Although the full QESM is still being assembled, the power of the approach has been demonstrated.

There is a strong heritage in the development and use of off-line CTMs in the UK. In the context of an ESM strategy, their role is twofold. First, they are an excellent, cost-effective tool for developing and testing schemes for use in ESMs. Thus, the p-TOMCAT and SLIMCAT CTMs have played an important role in the development of UKCA. They use fields of temperature and winds (and possibly sub-grid scale parameters) from global NWP models constrained by observations by using data assimilation (so-called reanalyses). Therefore, off-line CTMs are excellent tools for testing the chemistry and aerosol modules for use in ESMs, being easy to use and providing direct comparison with observations. Secondly, they remain an excellent tool for scientific research and can potentially push research boundaries further than in a complex ESM, pointing the direction for future ESM science and development.

The community has, for the most part, adopted the TOMCAT family of off-line chemical-transport models (TOMCAT/SLIMCAT/GLOMAP/pTOMCAT) with considerable success for tropospheric and stratospheric studies.

6.2 Issues

Current UKCA developments are well suited to centennial scale investigations. More effort is required to address very long timescales and more complex schemes for short integrations (e.g. to address air quality issues).

More effort is required on emissions, including both natural and anthropogenic emissions and coupling between land/atmosphere and ocean/atmosphere. Regarding natural emissions, the MEGAN/JULES/UKCA combination of models provides a good basis for continued development for the land surface. The PlankTOM10/UKCA combination provides a good basis for continued development for the ocean. QESM has provided a framework for these developments to date.

6.3 International Context

Internationally, there are a number of atmospheric chemistry models available for use. For example, the GEOS-Chem chemical-transport model, developed by the University of Harvard, is used by some UK researchers (mainly those who have worked in the US). It is based on very similar principles to the TOMCAT model, though with an emphasis of detailed tropospheric chemistry. It is well supported and generally easy to use.

There is no significant take-up of international chemistry-climate models by UK researchers. The schemes developed in CTMs for use in UKCA are all internationally competitive. Furthermore, UKCA has been developed in such a way that it is possible for the user to install their own (or off-the-shelf) chemistry or aerosol schemes.

6.4 Strategy

The development of UKCA together with common chemical/aerosol transport modules must be supported. These modules will first be developed off-line but have a commonality with the schemes used in ESM (and wider scientific studies outside of the ESM).

Further resources to help create a more easy-to-use and well supported model is a very high priority. The main reason why other models are sometimes used relates to ease of use.

Attention needs to be given to developing well-founded surface exchange schemes for natural emissions (terrestrial and marine).

6.4.1 Medium term strategy

UKCA is a key component of QESM and will be the major chemistry/aerosol module for that model for at least the next five years. CTMs will continue to play an important role, with the aim of developing common modules for a hierarchy of atmospheric and ES models, and for opening new areas in atmospheric chemistry and aerosol research.

While the present focus in UKCA is on centennial scales, effort needs to be devoted to developing schemes for shorter and longer timescales (see 6.2).

The ESM must have a sufficiently realistic tracer advection scheme to be able to represent the inhomogeneous distributions which occur in active chemical tracers. UKCA has suffered from some issues with the advection scheme in the host climate model (the UM). The pragmatic solutions adopted so far are not optimal. A new tracer advection scheme is a priority in the medium term.

6.4.2 Long term vision

Atmospheric chemistry and aerosol processes will certainly remain central to global change. A longer term challenge will be to develop models with the flexibility to address a range of issues on vastly differing time scales and which can rise to the challenge presented by vast, inhomogeneous data networks.

6.5 Interfaces

Development of aerosol/chemistry schemes for ESM needs to interface with researchers active in modelling of composition. The planned modules should be based on common tools which can become UK standards.

Exchanges with the land and ocean surfaces are critical and in many cases poorly understood. Therefore there needs to be more emphasis on collaborations between the atmosphere/land and atmosphere/ocean communities.

6.6 Implementation Pathway

Past work has laid the foundations for composition modelling in this area.

Funding is needed to enable development of core chemistry/aerosol modules for the hierarchy of models, feeding into ESM. Model development and code maintenance such as this needs to be core funded (i.e. not responsive mode) and be allocated to groups with expertise in these areas. The chemistry/aerosol schemes themselves need to be based on tools already developed and used in the UK community – e.g. chemistry based on ASAD solver and GLOMAP aerosol scheme.

In addition more effort is required regarding exchanges with the land and ocean surfaces and the coupling between atmosphere/land and atmosphere/ocean.

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 Current Capability

The state and evolution of the land surface play a fundamental role in the Earth system. The fluxes of energy and water from the surface into the atmosphere control the recycling of water over the land surface and large scale atmospheric circulations. The terrestrial biosphere absorbs approximately one quarter of anthropogenic CO_2 emissions and also is a source (and sink) for many atmospheric chemical species important to the radiative balance of the atmosphere (CH_4, N_2O, VOCs, aerosols etc). The land surface is also central to the major effects of climate impacts especially in terms of water resources and ecosystems.

JULES (Joint UK Land Environment Simulator, http://www.jchmr.org/jules/index.html) is the land surface model widely used within the UK. It is the land surface component within the latest Met Office Unified Model and is within the HadGEM2 ESM. The latest version of JULES is modular and is evolving towards being FLUME compliant (see Section 0). QESM is currently working on putting JULES into a FLUME framework in order to couple it to HadGEM3. JULES can also be run off line, either at a single point or driven by global climate data (such as the WATCH forcing data). It is also interfaced into the IMOGEN global climate impacts model[2] that includes a weather generator.

JULES has been turned into a community model; jointly supported by the MO and CEH and managed through subject theme leaders and a Management Committee.

JULES has made major advances through the QUEST programme. New components for soil biogeochemistry (ECOSSE), vegetation nitrogen (FUN), agriculture/crops, vegetation dynamics (ED), biogenic emissions model (MEGAN) and fire (SPITFIRE) have been obtained. These components have been combined into a new version of JULES which will be incorporated into the QESM (and will be part of JULESv3 to be incorporated in HadGEM3). QUEST has also funded protocols and data for benchmarking and testing the JULES at site and global levels.

There are a number of other global vegetation and biogeochemical models used within the UK, notably LPJ, HYBRID, SDGVM. These typically include more complex vegetation descriptions and are very valuable for off-line global analyses but none can be completely coupled into a complex ESM.

7.2 Issues

The very valuable science components recently incorporated into JULES will need further analysis and development in their fully coupled mode. There are a number of challenges at present:

- The community support for JULES, currently two FTEs funded jointly by the MO and QUEST (based at CEH), needs to be expanded and put on a secure footing.
- There is a lack of computer-model literate environmental-science students leaving university and entering the PhD programmes. The science level in higher-education is high, but is not linked to modelling skill, which is more prevalent in the physical sciences,
- The interface of JULES to the other components of the Earth System (notably atmospheric chemistry, ocean biogeochemistry and ice) need more attention.

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[2] **IMOGEN (An intermediate complexity climate model for impacts scenario generation) is a** computationally efficient modelling system designed to undertake global and regional climate change impact assessments. A pattern-scaling approach to climate change drives a gridded land surface and vegetation model (JULES). The structure allows extrapolation of General Circulation Model (GCM) simulations to different future pathways of greenhouse gases, including rapid first-order assessments of the land surface and associated biogeochemical cycles.

- Components of JULES need including or updating, for example permafrost, groundwater, macronutrients, vegetation dynamics, river chemisrtry (incl sediments).
- New datasets are needed to develop and benchmark JULES – particularly distributed global and regional sets.

7.3 International Context

Internationally there are a wide range of land surface models (for example LPJ/LPX in Europe and Australia, ORCHIDEE in France, CLM in USA, CABLE in Australia etc). Each of these models has strengths and weaknesses in both the science and governance. A number of intercomparison programmes (PILPS, C4MIP, WaterMIP etc) have highlighted a wide range of responses in different components (carbon, runoff etc). An initial comparison of a selection of these models against global carbon and water data (code named: iLAMB, reported to the EU ENSEMBLES project) demonstrated that no single model can be said to be superior. In fact sectorial comparisons suggest different models do better in different parts of the world or for different timescales (e.g. seasonal, interannual variability or trends). The UK has a strong environmental science base and there is a good case for exploiting this to improve the UK land surface modelling capability. The community across UK science institutions that has been built up over the last few years in developing JULES is a valuable resource to this end – enabling good pull through from the academic sector to the operational sector (Met Office). JULES is probably within the world leading group of land surface models (but maybe not the world leading model): to maintain our current status will require continuing development and investment.

7.4 Strategy

7.4.1 Medium term strategy

It is recommended that JULES remains the land surface model of choice within NERC and the component of a NERC/Met Office Earth System Modelling System. The technical support (joint between CEH and MO) needs to be continued and enhanced. In the short term (up to 3 years) work in needed to consolidate the new science components (primarily generated by QUEST) into JULES and ensure their correct perfomance within QESM. Data assimilation into JULES, both for improved parameter estimation and to provide initial states of seasonal and decadal forecasting will need to be developed further.

7.4.2 Long term vision

In the longer term the JULES community needs to continue to consider alternative and novel approaches (for example in vegetation and hydrological modelling). JULES is already a system with multiple options, this aspect should be developed by providing a degree of internal modularisation with the ability easily to accommodate new or alternative process descriptions. This will enable JULES to incorporate new and emerging science more easily. JULES can also act as an impact tool on- or off-line from the ESM – this aspect needs further development to understand issues of scale and model biases. The links to simple climate models (such as IMOGEN) and off-line data sets (such as the WATCH data sets) are an important component of JULES, the development of an ESM framework and coupling tool will greatly help JULES , both in development phases and in its use as an impacts tool.

To improve the development of JULES, we need to raise the capability in the UK of model-literate students in the environmental and biological sciences. A possible route is to use JULES as a training tool and encourage its use within MSc courses. Some small investment in IT would be required to achieve this.

7.5 Interfaces

The primary interface of JULES is through the atmosphere. The exchanges of energy, water and carbon dioxide are well described but the parameterisations of trace gas fluxes are very new (MEGAN) and need more development to fully interact with the atmospheric chemistry models (see Section 6). JULES should also interface with the ocean biogeochemistry model. JULES currently routes the grid scale runoff through a river network to the ocean without the possibility of horizontal transport between grid cells. Currently freshwater chemistry is not modelled but it could be accommodated into the existing structure. There is currently ongoing activities to include land ice in JULES and there is potential to integrate more closely with the ice sheet component. Anthropogenic influences are very important to the land surface. There is already continuing work to include agriculture and water impoundments into JULES. To provide a fully interactive model which include changes in land use, agriculture, emissions and water use JULES would require coupling to social or economic sub-models. In the short term it is unlikely this can be achieved and we will have to rely on off-line forcing however this should be kept as an option for longer-term development.

7.6 Implementation Pathway

It is recommended that the existing governance structure is retained, with the addition of a NERC representative (eg Theme Leader) on the JULES Management Committee. New developments and validation should be undertaken under NC and/or RP funding. In the long term the code will need to be restructured, probably by a software engineer, to make in more flexible. The primary support should continue to be a joint MO/NERC partnership and could come under the JWCRP (the JCHMR based at Wallingford facilitates this). Data is, and should be, be an integral part of JULES, the use of EO datasets for development and validation should be expanded.

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 Current Capability

Until recently ocean modelling in the UK has centred around using versions of the GFDL MOM (Modular Ocean Model) code. This has provided the ocean component of ocean forecasting and climate models at the Met Office up to and including HadGEM2 (including HadCM3 and lower resolution models such as FAMOUS), and versions of the Unified Model (UM) up to and including version 6. It also provides the ocean component of the high-resolution HiGEM climate model. NERC and the Met Office currently retain a significant investment in this older „UM" ocean model, since the HadGEM2 and HiGEM models will be used for the UK"s input to the IPCC AR5 exercise.

However, the focus of the UK effort is now moving to the NEMO ocean modelling system. NEMO (or more accurately its subcomponent ocean model OPA) is currently the key model for the physical ocean in the UK, and plays a leading role in Europe. Although originally developed in France, it is now maintained through a consortium involving the Met Office and NERC, and both UK partners invest considerable effort in its ongoing improvement. NEMO is now the ocean component of systems at the Met Office for both operational ocean forecasting (in the FOAM system) and climate prediction on a range of timescales (i.e the HadGEM3 family of models, and the QESM earth system model), and this effort is underpinned by both NOC in Southampton for the global ocean and Liverpool where a shelf version of NEMO is being developed. The HadGEM2 and HiGEM models will be phased out with the move to a NEMO ocean.

NEMO is an open source, modular modelling system with a very large worldwide user base. It is relatively easy to use and is applicable to high-resolution global ocean modelling, coupled climate modelling, and for paleo studies. It is possible, for instance, to complete a model integration of order 10,000 years (with a 4° resolution global model) for paleo studies in an elapsed time of order 1 week on a single fast vector processor (e.g. NEC SX8). In addition, NEMO has an automatic tool (AGRIF) for two-way nesting (with multiple levels of nesting being possible) making it particularly suitable for very high-resolution regional modelling of, for instance, shelf and coastal areas. While initially developed as a vector optimised code with reasonable speed on massively parallel (MPP) computer architectures, effort is now being directed to optimise NEMO for the MPP machines. Even so, scalability on massively parallel computer systems is generally good (with thousands of processors often used effectively), but this is insufficient for the expected needs for ~10^5 processors in the near future.

As for data assimilation in NEMO (more details of which are described in a separate Section 17), a Linear-Tangent and Adjoint (TAM) model now exists for version 3.0 and will be implemented in the NEMO system in 2010. This provides the inner-most loops for variational data assimilation techniques (by allowing the model to run backwards and forwards in time). Additional work to undertake 3D- and 4D-VAR data assimilation in NEMO (i.e to provide the outermost loops to calculate the variational increments) is being undertaken by the NEMO-VAR consortium (in which the partners are the UK Met Office, CERFACS, ECMWF and Grenoble University).

Other important ocean models in the UK are POLCOMS, HyCOM, FVCOM, ICOM and GOLDSTEIN. POLCOMS is adapted to specialised processes in the shelf seas. It has been developed by NOCL and is operational in the Met Office ocean forecasting systems. HyCOM is an ocean model with a largely isopycnal coordinate system and offers potential advantages (such as enhanced water mass preservation) over the "level" coordinate ocean models such as standard versions of NEMO. This is being explored in a coupled climate model (CHIME) at NOCS. FVCOM is a finite volume coastal ocean model using triangular unstructured grids in the horizontal and s-coordinate layered grids in the vertical. It is less sophisticated than ICOM but at a more advanced stage of practical application. This is in use at NOCL. ICOM is potentially a "next generation" ocean model that offers world-leading potential with an unstructured and adaptive grid (which places extra resolution where needed by the evolving flow field). This model is currently under development at Imperial College, with support from NERC through the SOFI (Strategic Ocean Funding

Initiative) framework. GOLDSTEIN is a frictional (or "planetary") geostrophic ocean model which has reduced physics but is extremely fast and designed for use in paleo-climate studies. It forms the ocean component of the GENIE Earth System Model of Intermediate Complexity (EMIC), which is currently widely used in the UK paleo community.

8.2 Issues

A major long-term issue is that the UK is still lacking a general ocean model that can be seamlessly applied to the open oceans and adjacent shelf and coastal seas with resolution and discretisation methods adjusted appropriately to the region/processes concerned. The shelf version of NEMO is under development at NOCL, for instance, but its structured grid constrains its flexibility and efficiency of application in coastal oceans with complex boundaries. This is also an issue for the ocean modelling community globally. A combination of structured and unstructured grids in the horizontal and hybrid z, s, and isopycnal grids in the vertical would be ideal for this requirement. The system needs to be accurate, efficient and readily usable by scientists from a wide range of disciplines. It will furthermore need to utilise the next generation of massively parallel computer systems which use 10-100k"s cores and new programming approaches. It is only in this way that we will be able to realise the goal of multi-scale eddy-resolving ocean-shelf-coastal modelling with applications to climate modelling, biogeochemistry (water quality), sedimentation, sea-level, and sea-ice, ice shelves, and ice sheets.

It is also recognised that there would be much benefit in the UK developing a new unified dynamical core for the most complex top level models of the atmosphere and ocean. This would enable development benefits to be shared between the two communities, so that, for instance, we would only need to optimise one such core on each new generation of computer architecture. In addition, a common framework could also be developed for data assimilation codes. This would have very significant savings in terms of resources, as well as acting as a catalyst for further integration of the two modelling communities. It is noted that such a development is already underway in the US with the MITGCM model framework.

The control of spurious numerical horizontal and vertical mixing is another key issue affecting ocean models. This impacts upper ocean water masses, surface temperatures and biogeochemical fluxes, and prevents simulations from realising the benefits of developments in sub-grid scale parameterisations that reflect the small-scale nature of many mixing processes. This requires the development of new and sophisticated advection and/or vertical coordinate schemes.

Finally, there is significant uncertainty surrounding the timescale for the development of ICOM as a practical ocean model for realistic applications. It offers world-leading potential but is currently some way from this position. Difficulties arise from the use of grid cells which are of high aspect ratio for a realistic ocean context, making the resulting solutions prone to being ill-conditioned. There are also potential problems with the control of numerical mixing due to the adaptive regridding process.

8.3 International Context

NEMO is a world-leading international ocean model with a wide user base, as already described. It is currently being developed by an international effort between France and the UK (incorporating a distributed systems team), together with Canada. Other major international modelling efforts (in the US) are the MITGCM model, layered/ isopycnal/ hybrid models such as GOLD and HyCOM, and FVCOM. Most of these modelling frameworks are able to address studies over a wide range of time- and space- scales (including paleo, climate, high-resolution global, and shelf/coastal applications). The MITGCM has a non-hydrostatic mode of operation, and the layered models generally have much reduced numerical mixing in the vertical. FVCOM is a terrain-following and horizontal triangular unstructured grid model, which can easily match irregular ocean boundaries and refine its local resolution. One distinct advantage of NEMO, however, is its ability for automatic two-way nesting, making it ideal for regional modelling studies which need very high resolution and which are not limited by open boundary conditions. This is also an advantage for processes involved in climate feedbacks. Furthermore, the NEMO community are now investigating new coordinate systems in the vertical which reduce numerical mixing, effectively ensuring that the model is isopycnal to high-frequency motions. This could lead to a fully isopycnal or hybrid version of NEMO in the future. The development of such coordinate systems is being informed by the use of HyCOM in the CHIME climate model in the UK. A non-hydrostatic option for NEMO could also be relatively easily developed if required.

8.4 Strategy

8.4.1 Medium term strategy

The UK strategy for ocean modelling should continue to focus on the NEMO system for the medium term (~ 5 years) at least. There is currently a large amount of effort being invested by the UK community in the development and operational use of NEMO, and no compelling reason to deviate from this intention. However, it is also important to be supportive of, and responsive to, the development of emerging modelling technologies such as FVCOM and ICOM, and assist their passage to operational models if they are proven to provide a better long term development path. HyCOM, already a proven technology, should be supported in the short-to-medium term through a low level effort at NOCS. This enables the UK to investigate "full-physics" climate models which are structurally different to those at the Met Office, and to inform on the process for the development of more generalised vertical coordinate systems in NEMO. There is currently an action in the second round of NERC‟s thematic action plan (TAP2) to undertake an assessment of long term user requirements and technical options for ocean modelling, delivering around mid-2012, and this is expected to critically inform on the requirements for and usefulness of ICOM and HyCOM. Finally, POLCOMS applications should transition to an equivalent system based on NEMO ("NEMO-Shelf") in the medium term, and thereafter POLCOMS should be maintained as a legacy code, as appropriate.

8.4.2 Long term vision

As part of the Next Generation Weather and Climate Prediction TAP2 action a specific task has been identified to produce a 10 year roadmap of requirements for ocean modelling. This will be undertaken by a 2-year PDRA who will work closely with existing NERC ocean modelling activity being undertaken as part of National Capability, and with the Met Office via the Joint Weather and Climate Research Programme. In particular, this action will inform the community on the requirement for scalable ocean model cores. If this identifies a specific need for work on a new ocean dynamical core, this will be brought to NERC as a separate action. It is also expected that this action will consider the rationale and feasibility of the UK developing a new ocean dynamical core which is equally applicable to atmospheric modelling, as outlined above.

In the longer term (e.g. 5-10 years), the UK should also develop a new innovative model with reduced numerical diffusion and which can be seamlessly applied to both the open ocean and shelf and coastal seas, as outlined above. This would ideally take the form of a general-grid model with the ability to use both structured and unstructured grids in the horizontal and z-, s-, and isopycnal grids in the vertical. An emphasis should be placed on the usability and ease of maintenance of the model, making it accessible to scientists from a wide range of disciplines. The model should be coded with an open and modular structure using the new features of modern programming languages.

8.5 Interfaces

The ocean model should be able to interface directly with models of the atmosphere, sea-ice, ice shelves, marine biogeochemistry and river runoff. While coupling with the atmosphere is usually through a coupler such as OASIS, models of sea-ice and marine biogeochemistry are often embedded within the ocean model code. River runoff is typically applied as a direct input to specified ocean model grid cells. The ocean models should also interface with more specialised models for applications such as, for example, search-and-rescue, oil spill prediction, and coastal sea-level and erosion.

8.6 Implementation pathway

Strategic directions for the implementation and development of NEMO will be initiated and maintained primarily through the Joint Weather and Climate Research Programme (JWCRP) between NERC and the Met Office. Specifically, this will build on a close strategic alignment of ocean modelling between NOCS and the Met Office which is already under way. This programme should be further expanded to include development of the NEMO-Shelf model at NOCL. Further integration of the NEMO-Shelf and global modelling will also continue to be achieved through the NCOF (National Centre for Ocean Forecasting) partnership between NERC and the Met Office.

The effort from both NOCS and NOCL for the development and maintenance of NEMO comes from NERC"s National Capability (NC) funding stream which is currently supported through the Oceans 2025 programme. This should be continued beyond the formal end of Oceans 2025 in 2012, and expanded as necessary.

HyCOM and FVCOM are also currently supported through the NC component of Oceans 2025. The ICOM model is supported through a NERC consortium grant (which is now coming to an end) and the SOFI initiative in Oceans 2025. Further support for ICOM should be sought, possibly in the form of an additional NERC consortium or Responsive Mode proposal, or perhaps through European funding. Longer term commitment to HyCOM, ICOM and other potential modelling approaches will be informed by the TAP2 review of long term ocean modelling requirements, reporting mid-2012.

Finally, major new innovative model development, for example to develop a new seamless model for ocean-shelf-coastal modelling, or for a common dynamical core for the ocean and atmosphere communities, would require significant new investment from NERC, either through the National Capability funding stream, or through new TAP actions.

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 Current Capability

Ocean biogeochemistry modelling is an area of rapidly increasing importance and global visibility, as it has been realised that there is a potential for climate change and rising CO_2 to have major impacts on marine ecosystems and these in turn could (a) have significant feedback effects on CO_2 and climate, and (b) add to the already serious stresses on fisheries. It is also possible that removal of top predators through fishing may impact on the biological carbon pump by inducing a trophic cascade.

A fundamental problem is to find the appropriate level of complexity that will enable ecosystem models to have the most skill in predicting biogeochemical fluxes. We must bear in mind that the level of complexity also depends on how well we can parameterise things; the quest for greater detail has to be tempered by our ignorance of the ecology and physiology of the organisms in question. There are a number of approaches currently in use in the UK, all of which run in the NEMO hydrodynamic framework and could be drawn on to improve and enhance the current Met Office model, known as diat-HadOCC:

MEDUSA is similar in structure but with more up to date parameterisations than diat-HadOCC. MEDUSA has two classes of phytoplankton (diatoms, non-diatoms), two zooplankton (micro and meso), two detritus (slow and fast sinking) and three nutrients (nitrate, silicate, iron). As such, it is relatively simple in structure but nevertheless incorporates sufficient complexity to address key climate feedbacks (e.g. associated with altered iron inventory).

PlankTOM is a global marine biogeochemistry model that includes an extensive representation of marine ecosystems (lower trophic levels) based on Plankton Functional Types (PFTs). The main goal of PlankTOM is to understand and quantify the interactions between climate and marine biogeochemistry (both impacts and feedbacks), particularly those mediated through CO_2 and marine ecosystems. The model represents the marine cycles of C, N, O_2, P, Si, and a simplified Fe cycle. The model estimates the air-sea fluxes of CO_2, O_2, DMS, and N_2O.

ERSEM (the European Regional Seas Ecosystem Model) is a mature Plankton Functional Type model which describes key processes of temperate shelf seas ecosystems; the main ones being some plankton community complexity, the microbial loop, variable nutrient stoichiometry, variable carbon:chlorophyll ratios and a comprehensive description of benthic biochemical and ecological processes. The units of currency of ERSEM are Carbon, Nitrogen, Phosphorus, Silicon, Oxygen and optionally Iron. There is an additional model which adds the sulphur cycle, via the biological production and fate of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP).

It should be born in mind that the choice of model is a function of the question being asked and that the model systems are also used to assess regional ecosystem response to climate change.

9.2 Issues

There are three key overarching sets of issues: technical and quality control; model development to resolve key processes in the earth system and the next generation of ecosystem models.

Technical and quality control includes issues such as: version control: model complexity and parameterisation; quality of the physics, the ability to produce an ensemble of ecosystem states and model benchmarking and validation and can be addressed by developing a common model framework.

There are a number of key processes which require further emphasis on model development, these include

- Marine Biological Carbon Pump: re-mineralisation of export production and meso-pelagic ecology.
- Ocean Acidification: physiological response to high CO_2.

- Air-Sea interface including parameterisations of gas exchange, marine biological production of climatically active gases and atmospheric sources of iron.
- Ocean-shelf exchanges of carbon, nutrients and biota
- Effective modelling in light-stressed regimes (thermocline and turbid environments)
- Land ocean interface, including resolving coastal physics, benthic ecology and biogeochemistry, linking to river catchment models (including nutrients).

These processes are likely to form a central component of a next generation community biogeochemical/ecosystem model. If we are to project ecosystem states and hence biogeochemical cycling beyond the current climate envelopes we need to develop models which can adapt (and possibly evolve) in response to environmental change. This may require new model strategies which take better account of physiology, foodweb plasticity, links to higher trophic levels and exploit the increasingly large amounts of genetic information.

9.3 International Context

There are major modelling efforts in several countries, notably the USA, France and Canada, and (crucially for the modelling efforts) an intensification of laboratory, mesocosm and field experimental research on plankton physiology and marine ecosystem dynamics. This is leading to a proliferation of models and the international community is currently divided regarding the most appropriate level of complexity for ocean biogeochemical/ecosystem modelling. The UK community is taking a lead in this debate.

9.4 Strategy

9.4.1 Medium term strategy (1-5yrs)

To address the key challenges of model structure, complexity and validation a common modelling framework is required which would provide: (i) commonality in model, physics, resolution and forcing, (ii) data and metrics to validate models; (iii) a common framework for data assimilation and (iv) ensemble simulations of ecosystem states. It is proposed that one core code should be configured that would be compatible with different biological modules (ERSEM, PlankTOM, MEDUSA etc), where the modules could be switched on or off depending on the complexity required. Emphasis would be placed on model inter-comparison in particular focusing on structural and parameter uncertainty. The strategy for process model development is to build on the current O2025 program as augmented by the Theme Action Plan RP research topics (e.g. Ocean Acidification, Arctic, Quantifying uncertainty etc…). The common core will also provide the framework for developing coupled ocean atmosphere ecosystem models.

9.4.2 Long term vision (5-10 yrs)

To address the issues identified in 9.2, the longer term vision is to develop a unified UK community biogeochemical ocean model of appropriate complexity. The same model would work at timescales from days to millennia, and at resolutions required for operational forecasting, ecosystem response to climate change and Earth System Modelling, whilst maintaining the ability to trace between the hierarchies of complexity (i.e. it would be downgradable to a simpler Nutrient Plankton Zooplankton Detritus NPZD type model) and the ability to assimilate physical biogeochemical data. 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. Such a model would describe amongst other things the cycles of carbon, macro nutrients, biogenic gas production, ocean acidification and shelf seas processes. This next generation model will be able to adapt (and possibly evolve) in response to environmental change. A particular challenge for such a framework would be to accommodate emerging novel approaches that significantly diverge in character from existing approaches e.g. statistical, evolutionary, cell-size based etc. In addition, we need to meet the research challenge of coupling next generation of ocean physics to models of marine biological processes. The development of the next generation of ecosystem models will require a coordinated initiative by the UK community.

9.5 Interfaces

There are three key interfaces with the rest of the earth system, the air sea, the land ocean and the benthic-pelagic. Of these only the air sea interface is regularly described in Earth System Models in any detail. For the strategy to progress the biogeochemical modelling community requires links with: the ocean physics community, the atmospheric physics and chemistry modellers, terrestrial ecologists, hydrodynamic/ river modellers and climate scientists.

9.6 Implementation pathway

Based on the discussion above the key steps in the implementation plan are:

- Establish the ecosystem model framework in NEMO
- Develop model benchmarks and metrics
- Implement data assimilation
- Develop the next generation ecosystem models
- Integrate biogeochemical models with the next generation physics

The assumption is that the process model development is ongoing and priorities driven in part by the consensus of the wider ESM community.

10.SEA FLOOR

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

10.1 Current Capability

Seabed processes are significant on a global scale. In the deep ocean they represent a sink for carbon from the ocean, and these processes are particularly significant on geological timescales. Up to 25% of the oceanic primary production takes place in shelf seas. Seabed processes are tightly coupled to pelagic processes and play a major role in the biogeochemical cycling of carbon, nitrogen, phosphate, silicon etc…) which drives primary production in these regions. In addition the seabed in shelf seas can act as both sources and sinks of macro nutrients. The seabed also significantly impacts on shelf seas carbonate chemistry.

The seabed is also a source of climatically active gases, most notably methane from methane hydrates. These are buried below the sea-floor as a waxy substrate but can dissociate under warming of the bottom waters from climate change, leading to methane outgasing to the atmosphere, and massive failures of the shelf slopes. Such release could therefore act both to accelerate global warming, and as a source of tsunamis to coastal communities. While various aspects of methane hydrates are currently under investigation, there is no known model of the complete pathway via which they are able to escape from the seafloor and reach the atmosphere.

The current generation of Earth System models does not include seabed processes. However the ERSEM marine biogeochemical model contains a benthic component which is capable of describing the biogeochemical cycling of C, N. P and Si in shelf seas.

10.2 Issues

There is a need for the development of a sub-component model to describe methane hydrates in the Earth system. This would involve cross-disciplinary interactions (eg with geologists) and would be a long-term development issue.

10.3 International Context

There is no strong leadership internationally in this area. This therefore provides an opportunity for the UK to take a lead. Links to the benthic process modelling e.g. in the Netherlands (Middleburg) would help strengthen this work.

10.4 Strategy

10.4.1 Medium term strategy (1-3 years)

The medium term strategy is to support and develop the ERSEM benthic model within the overarching biogeochemical modelling framework.

10.4.2 Long term vision

The long term vision is to develop specific process models of methane hydrate and other sources of climatically active gases from the seabed. These eventually could be included in ERSEM or exist as stand-alone modules.

10.5 Interfaces

Sea bed process models should be directly interfaced with coupled physical biogeochemical models of the overlying ocean.

10.6 Implementation pathway

The shelf seas benthic model should be included in the ocean biogeochemical framework.

The hydrate modelling should benefit from the NERC Arctic program. However, the development of an operational hydrates model would require additional development.

11.SEA ICE

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

11.1 Current Capability

Current UK capability in sea ice modelling centres around two systems: CICE from the Los Alamos National Laboratory (LANL) in the US, and LIM2/3 from Louvain-La-Neuve in Belgium. These models are broadly similar in physical capability (both having elastic-viscous-plastic, EVP, rheology for their dynamics – in the case of LIM3 and CICE) but with some differences (such as a representation of ice salinity in LIM). While CICE has been taken up as the model of choice by the UK Met Office, LIM is the sea-ice model which comes bundled as part of the NEMO system (which also provides OPA, the key physical ocean model for the UK). Both LIM and CICE are in use throughout the NERC centres in the UK. LIM is maintained as part of the NEMO system through a consortium involving NERC (NOCS), and model improvements are passed back to a central repository. CICE is similarly maintained, with the Met Office able to pass back improvements to the central repository in the US.

11.2 Issues

The sea-ice modelling community is thinly spread in the UK (NCEO/CPOM, NOCS, NOCL, BAS, Met Office). To maximise its effect and pull-through to operational modelling, its effort needs to be better coordinated.

One key outstanding issue is to clarify the route through which the NERC centres will be able to pass model improvements directly to the CICE repository. Currently the Met Office is formally able to do this through its agreement with LANL, but the NERC centres do not yet benefit from such an arrangement. This might be achieved either through a direct agreement between NERC and LANL, or by channelling community CICE developments through the Met Office. In either case a simple configuration management protocol needs to be agreed, so that developments can be pulled through to the CICE trunk with minimal re-engineering costs.

Further, it would be beneficial to develop a C-grid version of the CICE model (currently only a B-Grid version exists) to aid in coupling this to NEMO (which, in common with other world-leading models, uses a C-grid for its horizontal discretisation).

For LIM, code governance and the relationship to the NEMO consortium are currently under discussion between the LIM team in Louvain and the NEMO consortium.

11.3 International Context

CICE and LIM have their origins outside the UK (in the US and Belgium respectively), but both are now being developed through international efforts which directly involve the UK. There is now considerable convergence in terms of the capabilities of these two models (CICE and LIM3), both of which are seen as world-leading although CICE has the wider user base. LIM3 has a prognostic model for ice salinity, while CICE has a more complex albedo scheme. There are other sea-ice models which use VP (Viscous-Plastic) ice rheology but these are not as advanced as CICE and LIM3 (which use EVP, Elastic-Viscous-Plastic, rheology).

11.4 Strategy

11.4.1 Medium term strategy

CICE and LIM model sea-ice as a “continuum”. As model resolution increases beyond about 50-100 km, such continuum approximations begin to become questionable and at resolutions beyond 10 km, break down altogether since individual ice floes are comparable to the domain size and their interactions become important. Sea-ice models based on “discrete elements” attempt to represent such interactions, and could offer an alternative to the continuum models in the medium-to-long term, but are not yet proven in long-term basin-scale simulations. Alternative continuum models based on anisotropic ice rheology (which realise ice weaknesses and strengths in certain directions to account for, e.g leads) are also available but require implementation and testing in realistic basin-scale ocean model configurations. Consequently, the UK should continue to maintain and participate in the development of both CICE and LIM, at least in the short-to-medium term (e.g ~ 5 years). There is merit in maintaining an ability to use both these models in an Earth System Modelling framework. However, the overall weight of the UK effort should now move towards CICE, to provide a stronger underpinning to the Met Office capability. This would involve transitioning recent improvements in the LIM model to the CICE repository, and a better coordination of the UK CICE community. In addition, the improvement of sea-ice thermodynamics, new schemes for sea-ice albedo (for instance the inclusion of melt ponds) and the dynamical coupling between the atmosphere, sea-ice and ocean through boundary-layer parameterisations are the top priorities for development on the short-to-medium term. A C-grid version of CICE should also be developed in order to allow natural coupling to the NEMO model (which also utilises a C-grid), and also to other major ocean models (i.e. the MITGCM and GOLD models both use C-grids).

11.4.2 Long term vision

Both anisotropic-rheology and discrete-element sea-ice models have so far only been tested in stand-alone idealised configurations but not coupled to basin-scale ocean models. However, both these types of sea-ice model will be needed in the future as ocean modelling becomes feasible at increasingly high resolution, in order to simulate small-scale processes in the sea-ice field (e.g. such as leads which develop on the scale of a few kms). It is recommended that additional UK effort is targeted at the development of both these types of sea-ice model in the long term.

However, anisotropic sea-ice models are closer to realisation than the discrete-element models because they are based on known continuum approximations and their coupling to the thermodynamic equations has been largely solved. These models could be available in basin- and global-scale ocean models in 5 years time, but the discrete element models would probably take longer, eg order 10 years. The main outstanding problem with the discrete models of sea-ice is their coupling to the thermodynamic equations.

11.5 Interfaces

Sea-ice models interface directly with the ocean and atmosphere, and may also need to couple with models of ice shelves. Since models of sea-ice are usually embedded within their parent ocean code, this will allow them to interface with models of (for instance) river runoff which would interface directly with the ocean model itself. Some aspects of surface/atmosphere coupling are currently handled by the UM atmosphere component. This inhibits the adoption of certain developments to the thermodynamic code (e.g. multilayer thermodynamics). A solution is expected to be implemented by the Met Office and CSIRO when resources allow.

11.6 Implementation Pathway

There is currently effort to maintain and develop the CICE and LIM sea-ice models through NERC"s National Capability (NC) funding stream which is presently supported through the Oceans 2025 programme, but funding for this ends in 2012. The current Arctic TAP action could provide some additional modelling activity, however further funding would be required to expand and coordinate UK sea-ice modelling activity.

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 Current Capability

The UK currently has two well-developed ice sheet models: GLIMMER-CISM and BASISM. The former was initially developed within the GENIE programme and is currently funded though NCEO and JWCRP. It is collaboration between the Universities of Bristol, Swansea and Edinburgh, as well as the Los Alamos National Laboratory and Community Climate System Model (CCSM) in the US. BASISM was developed within BAS, and is used by BAS staff and associated UK projects. The degree of sophistication of the models‟ ice physics is similar, although GLIMMER-CISM has a more developed coupling interface.

12.2 Issues

The two models have different aims and uses. BASISM is primarily aimed at the improvement of process understanding and the development of the advanced numerical techniques needed to address issues such as ice-sheet initialization and grounding line migration (supported in part by the EU ice2sea programme). BASISM is targeted at groups who have the need of ice flow modelling without needing a fully-coupled ESM, for example the analysis of ice internal stratigraphy. GLIMMER-CISM is aimed at application to sea-level rise issues within the context of the Hadley Centre‟s suite of models. Overall, ice sheet modelling has received relatively little funding compared to other topical areas, and rather few coupled experiments have been run. This is despite a clear need for better sea level prediction, as well as a better assessment of ice sheet input within the long palaeoclimate simulations currently taking place.

12.3 International context

Since being released as an open-source code, GLIMMER-CISM has been taken up by a wide range of international groups. Most importantly, it has been adopted by the US Community Climate System Model‟s (CCSM) ice-sheet component with a first release of the coupled code in Summer 2010 (in the Community Earth System Model CESM). The UK developers of GLIMMER-CISM maintain close links with US collaborators within the CCSM group (most notably at Los Alamos National Laboratory) and hold three of the six seats on the GLIMMER-CISM steering committee.

In the last year, the US has invested heavily in the area of ice sheet modelling with the Department of Energy‟s ISICLES programme ($ 9M over three years), which involves many of the US National Laboratories. Three of the six ISICLES projects will make developments within the GLIMMER-CISM framework and are likely to have strong UK involvement. Nonetheless this level of investment means that the UK community faces the real threat of becoming marginalised in this area of traditional strength.

There are several examples of ESMs with coupled ice sheets in existence, although they tend to involve models of intermediate complexity (for instance, the Belgium LOVE-CLIM, German CLIMBER-2 and Canadian UVic models). Models that combine the appropriate physical treatment of ice sheets (e.g., incorporating longitudinal stresses) with a full treatment of atmosphere and ocean dynamics are under development in several countries but are not yet fully operational.

12.4 Strategy

Ice sheet models are currently in a crucial phase in their history: old theoretical limitations (e.g., robust grounding line migration) are being overcome and new numerical techniques (e.g., adaptive meshing) are being exploited. Closer collaboration between the developers of GLIMMER-CISM and BASISM is encouraged, perhaps 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.

12.4.1 Medium term strategy

The large resource devoted to ice sheet modelling in the US (above) and the potential threat to our impact in the medium term, are strong motivations for improved resource in this area. The US effort relies on linking the high-level of expertise in numerics and software design available within the National Laboratories to ice sheet modelling groups; a similar approach would be beneficial in the UK.

- Integrate GLIMMER-CISM coupling within new ESM framework, in particular migrate coupling to chosen software coupler. Design a compatible interface to drive BASISM where possible to permit modular use of ice-sheet models within the ESM framework.
- Improve numerical algorithms, in particular by developing the means of combining necessary accuracy or resolution at the ice sheet grounding line (100m to 1km) coverage of whole ice sheet (14×10^6 km^2 for Antarctica).
- Develop models for processes affecting ice sheet interaction with other elements of the climate system, in particular calving.
- Continued commitment to both the maintenance and development of GLIMMER-CISM software and the integration of BASISM with field data acquisitions.
- A commitment to improving modelling of basal processes guided by future developments and progress in the imaging of ice-stream beds.
- Continued development of strategies to be used in model initialization as the quantity and quality of data improve.
- Optimize coupling strategy between ice sheet and other components of the ESM; exploration of effects of asynchronous coupling and effect of simplified models of the other components.

12.4.2 Long term vision

- Development of data assimilation capacity within GLIMMER-CISM appropriate for both short (satellite) and longer term (geomorphology) data. Continued development of these themes within BASISM, with an emphasis on inverting internal stratigraphy and modelling geological observables.
- Improved representation of physics involved with mass and energy fluxes from other components of the ESM. Fuller representation of ice-shelf cavities in ocean model (NEMO). More complete representation of surface mass balance.
- Move towards unstructured grids (ICOM?).

12.5 Interfaces

The ice sheets interface with atmosphere, land and ocean. Until recently, ice sheet models tended to have their own surface mass balance calculation, however with the incorporation of a thorough snow model into JULES a more efficient route may be for JULES to compute surface mass balance and pass this information to the ice sheet model (developments underway at the Hadley Centre). Recent observations strongly suggest that oceanic change is a major driver for the ice sheets. Work within NCEO and JWCRP is aimed at developing an ice sheet-ocean coupler. Ice sheets influence atmosphere and ocean by changing their vertical (i.e. surface elevation) and lateral extents. Work on the completion of the ice-sheet components of global isotope cycles is also necessary.

Currently GLIMMER-CISM uses its own coupler to exchange information with the host ESM (examples includes FAMOUS, GENIE, HadCM3 and, shortly, the US‟ CESM). The move to an integrated ESM framework proposed in this report suggests that the current ad-hoc coupling should be incorporated into the chosen ESM coupler.

Recent research has shown that sections of the ice sheets may respond on decadal time scales, however many key scientific issues involving the ice sheets require centennial (e.g., future sea level rise on the time scale of response management), millennial (sustainability of the current ice sheets) and longer (glacial-interglacial cycles) simulations. It is therefore critical that the ESM framework provides atmosphere and ocean models that are capable of running over all of these time scales (see section on EMICs).

12.6 Implementation Pathway

The developers of GLIMMER-CISM and the Hadley Centre already collaborate closely (within JWCRP as well as the ice2sea programme). GLIMMER-CISM, for which there is already a coupling framework, therefore appears to be the logical delivery pathway to the wider Earth System Modelling community. Ice sheet modelling is currently in a state of rapid development (largely prompted by a revolution in the quality of data available through satellite observation) and major developments in the simulation of ice streams and grounding lines are likely in the next five years. Both BASISM and GLIMMER-CISM will play prominent roles in these developments. BAS, as the major funded source of NC in ice dynamics and ice-ocean interactions can be called on to provide support for future developments, augmenting NCEO, JWCRP and other future RP effort. A first step would be to implement a group, widened from the present GLIMMER-CISM team, to plan future improvements.

13.ESM COUPLERS

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

13.1 Current Capability

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.

OASIS has been developed and is maintained by CERFACS

http://www.cerfacs.fr/3-26568-OASIS.php

Some ESM components are currently coupled directly through merging of source code (e.g. UM/JULES). This has advantages in terms of computational efficiency and allows frequent coupling, but entails a re-engineering cost each time one of the component models is updated. For that reason, the QESM project is developing a FLUME-based interface between JULES and the UM atmosphere model.

13.2 Issues

For some components that use the same grid and time step, coupling at high frequency through OASIS may be computationally inefficient compared with combining those components in a single executable (e.g. ocean and sea ice). Thus there is a trade off between interoperability and computational cost.

In cases where individual ESM components are combined into single source codes (e.g. UM/JULES) there is a recurrent software engineering cost in maintaining up-to-date versions in both coupled and offline forms.

The central OASIS systems team has not had stable strategic funding.

Currently no formal governance structure exists allowing UK users requirements to be built in to development plans or resourced.

13.3 International Context

The OASIS coupler is widely used internationally. 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.

13.4 Strategy

13.4.1 Medium term strategy

In the short and medium term, NERC will engage with the OASIS team and other stakeholders to explore the possibility of developing a more formally managed and resourced development programme. This may entail a NERC contribution.

13.4.2 Long term vision

The longer term development of couplers will be considered as part of the ESM framework (Section 0).

13.5 Interfaces

Common strategy needs to be agreed with all partners who control individual component models. This will vary in difficulty among components, but for a number of existing European components may have been largely done through EU PRISM programme.

The strategy for UM atmosphere is particularly critical and needs to be agreed with Met Office.

13.6 Implementation pathway

The main actions are to:

- Engage with the Met Office to agree common interoperability goals and approach to the modelling framework (2010).
- Engage with the OASIS team and other stakeholders to explore possibilities for more robust long-term support, and required management structures.

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.

Note: This section should be read after sections 2 and 3 to give its strategic context.

14.1 Current Capability

The UK has a unique capability in the HadCM3 family of climate models (meaning, essentially, UM version 4.5 or 4.7 physics packages at various resolutions, comprising HadCM3, HadCM3L, FAMOUS, HadSM3, HadAM3P, HadRM3) due to the achievement of the Met Office in the mid-1990s in building a model that was, in terms of its climate simulation, at least ten years ahead of its time. These models are sufficiently fast and efficient in their use of memory to allow the following classes of investigation that are not currently possible with the HadGEM family:

- Perturbed physics ensemble simulation for quantifying uncertainty in model-based climate predictions (the QUMP/UKCP09 and climate*prediction*.net projects).
- Simulation of pre-instrumental climate, including the past millennium, Holocene, glacial-interglacial cycles and climates of the deep past (EU MILLENNIUM project, QUEST-ESM infrastructure and QUEST research Theme 2 projects).
- Risk analyses for low probability, high impact events, focusing on coupled processes and requiring large ensembles (the RAPID-RAPIT project).
- Large ensemble simulation with regional climate models for risk analysis of regional climate change, allowing user specification of region, resolution and diagnostics (PRECIS project).

The baseline HadCM3 model has also been extensively analysed over many years, so its performance, strengths and weaknesses are thoroughly documented. For ESM purposes, the HadCM3 family been equipped with submodels of the terrestrial and marine carbon cycle and coupled to the Glimmer-CISM ice-sheet model.

14.2 Issues

The wide range of projects continuing to make use of the HadCM3 family indicates there continues to be a scientific value for a model of this class, but the code is currently largely independent of HadGEM, depending on UM versions which the Met Office regards as obsolete, a different (and out of date) code management system and requiring significant NCAS resources for its continued maintenance on a range of platforms. It is also increasingly difficult to trace results based on HadCM3, such as estimates of climate and Earth System sensitivity, to HadGEM models as physical parameterisations continue to evolve.

The modelling and development environment for HadCM3 is subject to the general criticism of the Unified Model that it is not particularly user-friendly. This is increasingly an issue since models of this class are widely used in graduate student projects, and once scientists are familiar with a particular modelling framework, they are understandably reluctant to switch. There is a clear need to provide an “entry-level” GCM in the UK-branded ESM family. This is currently provided by HadCM3 class models, and a robust replacement with well-documented scientific performance will need to be available before support for these models can be discontinued.

14.3 International Context

There are two classes of international users of HadCM3 and related models. A relatively small number of international partners (e.g. in South Africa, Australia, New Zealand, Canada) make use of the full model functionality for research purposes on a range of platforms, precisely as UK academic users do. These users have made a substantial investment in this model, and should clearly be consulted on any decisions regarding its long-term support. Most are also potential or actual users of the new UK ESM, and hence would be likely to support a transition to using the new ESM when versions allowing the full range of experiments currently possible with HadCM3 are available.

The second class of international user makes use of a relatively “pre-packaged” version of the HadRM3 regional model for climate change impact assessments under the DFID-supported PRECIS project. Long-term support of these users is clearly essential, but their requirements are very different from those of research users. Support for this class of user is beyond the scope of this strategy, but their requirements, including a capability of running relatively high resolution at moderate cost by eliminating irrelevant processes, need to be considered in future model developments.

14.4 Strategy

14.4.1 Medium term strategy

We anticipate the HadCM3 family continuing to be chosen by researchers looking for a robust and inexpensive, albeit not necessarily state-of-the-art, model. Projects using HadCM3 could be supported by maintaining a limited number of model versions supported on a limited number of platforms. The existence of an implementation under the BOINC “middleware” distributed computing platform could be used to provide broad cross-platform support with limited resources.

Any further development of models in the HadCM3 family should be focussed on parameterisations that could be shared with the HadGEM family to enable transferability. The substantial experience in parameter sensitivities of HadCM3 through various perturbed-physics experiments, and the high cost of repeating these experiments with HadGEM, suggests a modest investment in transferring results (identifying corresponding parameterisations and establishing how well sensitivities map across between the models) would be highly cost-effective.

The user requirement for ongoing maintenance of HadCM3 configurations should be reviewed annually, because maintenance is expensive. A particular decision point will come with the implementation of the flexible ESM framework (Section 3). The cost of re-engineering HadCM3 into this framework is expected to be high, while there will be substantial scientific disadvantages of not being within it.

14.4.2 Long term vision

At any point in time, a version of the current ESM family is needed that runs fast enough to allow a range of experiments that are not accessible to „operational‟ models. Examples include large ensembles (including ensemble-based data assimilation), long runs (e.g. palaeoclimate) and large parameter sensitivity studies. Such a model needs to have a proven and well-documented climatology that is an adequate baseline for a wide range of applications. The model also needs to be computationally robust, so that it can provide an “entry-level” GCM that is accessible to new users. This is particularly important since as the performance of competitor climate models improves, ease-of-first-use will become increasingly critical in investigators‟ decisions regarding which ESM family to adopt. The pathway to this long term vision is described in Sections 2 and 3.

14.5 Interfaces

HadCM3 has currently (2010) been coupled to ocean and land carbon cycle models, and to the GLIMMER ice sheet model. Where robust model configurations of this type exist with a wide user base, they should be considered for maintenance under 14.4.1. Development of *new* couplings to HadCM3 should only be supported at project or programme level, according to specific scientific need.

14.6 Implementation Pathway

The development of a proven, computationally cheap ESM version directly traceable to current operational versions should be a priority, to allow extensive support of HadCM3 to be wound down (see Section 2). One option for maintaining HadCM3 during the development of a computationally cheap version of the current ESM family would be to focus support activities on supporting an open-source user community.

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 Current Capability

Earth System Models of Intermediate Complexity (EMICs) offer an important compliment to the more comprehensive (but computationally expensive) models discussed in Sections 2 and 14. They are particularly useful for longer (greater than a few hundred years) climate simulations required by the ice-core and paleo-climate communities, without necessitating asynchronous coupling. They also offer a relatively simple, easy-to-use test bed for implementing new Earth System Model components (eg ice sheets and marine biogeochemistry).

The main UK activity in this area is based around the GENIE model (FAMOUS was mentioned in Section 0 and has close affinity with the UM). GENIE was developed by a consortium of eight groups within NERC‟s e-Science programme; subsequent development was funded through the NERC GENIEfy project. GENIE has a large user community and has been taken up by researchers in the US and elsewhere. It has been used to study a range of paleo-climate problems from glacial-interglacial cycles to million-year integrations, and is the basis of some very innovative work using large (1000 member) ensembles to both optimise model components and assess the effect of parameter uncertainty on climate prediction. It has been important in analyzing uncertainty in CO_2 stabilisation scenarios and was featured in the IPCC (2007) report.

Key components of the system of model components that GENIE has become include: an energy moisture balance model of the atmosphere (EMBM); the IGCM primitive equation model of the atmosphere; the GOLDSTEIN ocean circulation model with a range of sea-ice models; a closed model of ocean-atmosphere biogeochemistry including terrestrial weathering and deep-sea sediments (ATCHEM/BIOGEM/ROKGEM/SEDGEM); and a number of land surface and vegetation models (e.g., ENTS, TRIFFID). In many respects, GENIE is a forerunner of the Earth System Modelling framework proposed in this report.

15.2 Issues

At present, the development pathway for GENIE runs in parallel to that of the UM-based Earth-system models discussed in previous sections, although resourced largely through the responsive mode. Some component models, such as those for the land surface and ice sheets, can operate interchangeably between pathways. The majority of the model components in the GENIE and UM-based pathways, however, remain bound to their respective base models. This situation is unsatisfactory for both scientific and resource-allocation reasons. Scientifically, a major hurdle to our ability to make predictions of future climate change is the assessment of the uncertainty associated with model structure (as opposed to initial conditions or parameter values). The effect of this uncertainty can only be assessed within a framework where individual model components can be accessed interchangeably, so that the bias which a particular component model introduces can be assessed within a coupled framework. In terms of resource, maintaining multiple development pathways is clearly inefficient.

15.3 International Context

GENIE is one of the most sophisticated EMICs in the international community and is unique in having an existing framework which allows components of different complexities. GENIE 1 (which uses an energy-moisture balance atmosphere) is comparable to many other models (e.g. the Canadian UVic model, or the Swiss BERN model). GENIE 2 (which includes a dynamic primitive equation based atmosphere) is unique and is at the forefront of EMICs. A few other models have geostrophic atmosphere models but GENIE remains the only complete EMIC with such a comprehensive treatment of the atmosphere, as well as the ocean, carbon cycle and icesheets.

15.4 Strategy

The overall conclusion of this report is that the UK should develop a single Earth System Modelling framework into which component models can be placed. GENIE contains several unique components that NERC should ensure are not lost to the wider community. It also offers the ability to make long-term climate integrations; again it is crucial that this capacity is not lost. A proposed strategy would therefore be to allocate resource to extract the key component models from GENIE and make them available through the developing model framework. Unique capabilities within GENIE include: the computationally-inexpensive EMBM atmosphere model (allowing long integrations); a similarly inexpensive low resolution ocean model; and a highly developed, coupled global biogeochemistry model (ATCHEM/ BIOGEM /ROKGEM/ SEDGEM).

15.4.1 Medium term strategy (5 year)

In the immediate future, the GENIE framework must be maintained. However, in the medium term new components need to be developed which work within the ESM framework. This will require the development of low resolution atmosphere and ocean dynamical cores, and is a non-trivial task potentially requiring additional parameterisations and extensive retuning. Existing higher resolution atmospheric cores (based on HadGEM and HadCM3) are unsuitable for any form of long term integrations. Therefore a different model structure will be necessary. Some basics research is required to identify the structure of the appropriate atmosphere and ocean cores.

Other unique components of GENIE, such as the long term ocean carbon and sediment cycle will need to be incorporated into the framework.

15.4.2 Long term vision (10 year)

The ultimate long term vision is to create an EMIC which provides a state-of-the-art tool for investigating Earth System history and performing large ensembles, using a system that seamlessly integrates with the spectrum of Earth System models. Such a vision is not easy to achieve due to the huge range of time and spatial scales.

15.5 Implementation Pathway

Implementation of the new framework should ensure that (a) the unique components of GENIE are not lost to the NERC community and, indeed, are made more widely available; and (b) the ability to conduct computationally-inexpensive climate simulations (for both long time scales and large ensembles) is not lost. The latter has implications for both the physical atmosphere and ocean components; which should ensure that viable reduced-resolution, as well as reduced-physics, models exist.

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 Current Capability

Earth System Models produce large volumes of data, but also depend on an input of data from observations. NERC maintains a strong capability in observations, through surveys, process studies, palaeoclimate and palaeoenvironmental studies, and remote sensing. In most cases, the products of these studies have not been specifically earmarked for use with ESMs. Benchmarking datasets, allowing model performance to be tested against the real world, have been developed for some ESM components: for example, for the land surface module, a number of data sets (including flux site data, runoff and atmospheric concentration measurements, and Earth observation products) have been identified and a protocol developed for their use.

16.2 Issues

Observations are central to Earth System Modelling: 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. Palaeodata, though generally sparse in space and time, potentially play a critical role in testing the response of models to changes over long timescales, and to a wide range of experiences. Given this crucial role of observational datasets described above, a modelling strategy should include consideration of what data are needed, and how they can best be organised for the above uses. This involves both scientific and data management issues: for example, turning sets of time series palaeodata into global databases for use with models is a major task, that is rarely easy to fund via open grant rounds, and creation of the correct products requires scientists able to sit at the interface between observationalists and modellers. Additionally many measurements are of proxies, rather than of the variables that are output from models: data-model comparison therefore requires either a conceptual model that deduces modelled variables from the proxies, or that forward modelling of the proxies is included in the ESM. While NCAS provides some support for generating ancillary files for UM simulations, and the NERC data centres hold some of the necessary datasets, in general there is little coordinated support for creating and providing the data requirements to run and test simulations.

16.3 International Context

There is an obvious international requirement for the same datasets for evaluation of different models, and there are numerous initiatives (such as the WMO GCOS or the ESA Climate Change Initiative) to ensure that appropriate datasets are collected and made available. Still, in many domains the provision of data in the format needed for the services described above requires extra effort. In the palaeo-domain, specific data initiatives related to ESM studies have been carried out for the Palaeoclimate Model Intercomparison Project (PMIP) and the Pliocene Research, Interpretation and Synoptic Mapping (PRISM). The UK has played a leading role in some of these initiatives, with QUEST most recently providing significant effort.

16.4 Strategy

The most important strategic goal here is to ensure the availability and use of appropriate datasets. This leads to a requirement that models must have the ability to interface with observations, that appropriate datasets are specified, and that they are then created in a suitable format. This requires effort on the part of both model and data providers, and recognition in funding calls of the need for more scientists happy to sit at the interface between models and observations.

16.4.1 Medium term strategy

In devising the proposed new ESM framework (see Section 3), the specification should enable datasets to be easily substituted in place of model components. This would allow the possibility to drive parts of the system with observations (as an example, the atmospheric chemistry module should be able to handle emissions generated by the land surface module, or those specified by inventory datasets). As part of the development of each model component, key initialising, benchmarking and validating datasets should be specified. For benchmarking, comprehensive and consistent datasets are required to enable comparison with models. Automated benchmarking tools have been developed to document the performance of climate models; this approach needs to be extended to ESM components such as the land surface, atmospheric chemistry, terrestrial and oceanic ecosystems. This makes it necessary for the community to agree on metrics of model performance.

For validation, many of the key datasets (including remote sensing and palaeodata) are in the form of observations or proxies that are not explicitly simulated by the model. We recommend that NERC (or JWCRP) resources should be used to develop appropriate modules to forward model key proxies, and that these should be included into the main ESM framework: water isotopes (a key palaeo proxy) are one obvious such module, but simulation of some of the observing systems used on satellite instruments would also be appropriate. On the other hand, while NERC generates many palaeo datasets, few of them are synthesised into the forms required for comparison with models, and this calls for specific activities to create such syntheses in appropriate form.

16.4.2 Long term vision

The medium term strategy calls for specification of datasets, syntheses, tools and forward modelling components that are needed. Provision of all these is likely to occupy the community for many years (in some cases requiring a long lead time). A longer term vision is that modellers and observationalists should design their tools and experiments with each others‟ needs in mind: in other words that the two communities should become more seamless in support of scientific understanding.

16.5 Interfaces

Data interface with every part of the ESM framework; each module, and the overall model, require data.

16.6 Implementation Pathway

The specification of important datasets that are needed is a relatively simple add-on for each component of the modelling framework. The strategic goal is to encourage close collaboration throughout the whole lifetime of the programme between observationalists and modellers to ensure effective and suitable provision of data to models and to provide model outputs to observationalists. There is considerable potential to use NC to expand the suite of benchmarking data sets for all components of the Earth System, including use of particular emerging products from the Earth Observation community. The development of forward models may be seen as a joint responsibility of the data and model communities; however, the maintenance of such modules within the ESM framework will require effort through the JWCRP. A more active recognition of the value of data synthesis activities, perhaps through a dedicated funding stream, or even a virtual centre in parallel with the modelling centres, would encourage the development of the appropriate datasets.

17.DATA ASSIMILATION AND MODEL INITIALISATION

Recommendation 17: Data assimilation must be developed as an integral component of the UK's strategic ESM.

17.1 Current Capability

Geophysical data assimilation is a quantitative, objective method to infer the state of the Earth system from heterogeneous, irregularly distributed data with differing accuracies. At its core is an ESM, which is used to synthesise our theoretical and prior knowledge with all available observational information. It has five key applications for Earth System Modelling:

- Determining initial conditions for forecasts with ESMs. The imperative for climate prediction is increasingly for predictions on regional spatial scales and on seasonal to decadal time scales. Accurate knowledge of the initial state is essential for such predictions.
- Testing climate models stringently against observational data. The heart of data assimilation is the regular comparison of model forecasts with data. This allows systematic errors in models to be determined and attributed, and allows a meaningful comparison between models and "observations of the day", e.g. from satellites.
- Determining model parameters by optimising the fit between forecasts with the models and observational data.
- Developing multi-decadal, internally consistent, global, gridded data sets ("re-analyses") to aid process understanding (e.g. of fluxes between Earth system components) and model development.
- Designing observing systems to assess the impact of new measurements and observational strategies on forecasts with ESMs and to assess their ability to discriminate model error.

Driven by the need for operational weather forecasting, data assimilation is well developed for atmospheric models. This development has gone in tandem with related improvements in the models themselves, and is a prime reason why atmospheric models are generally more advanced and more thoroughly tested than models of other components of the Earth system. Four-dimensional variational data assimilation is now used by the leading weather forecasting centres, which allows asynoptic satellite radiances to be assimilated directly, with demonstrable improvements in the forecasts. Assimilation of atmospheric composition measurements in coupled chemistry-climate models is developing, but currently of limited scope. Only water vapour and ozone measurements are commonly assimilated "on-line", but "off-line" assimilation of a wide range chemical species in chemical-transport models (including aerosols) is advancing rapidly (e.g. under the auspices of the MACC project led by ECMWF).

The need for seasonal forecasts with coupled atmosphere-ocean models has driven a concerted effort to develop data assimilation methods for ocean models, in order to take advantage of observations from satellite-borne radiometers, altimeters and scatterometers, and of in-situ measurements form the ARGO system of ocean buoys. Currently the most common assimilation method is optimal interpolation, though many research groups are moving toward the 3D-variational approach, in part to achieve some uniformity with atmospheric data assimilation. Besides observations of physical parameters, observations relevant to the biogeochemistry of the oceans are now being assimilated, in particular optical measurements to infer phytoplankton concentrations. This latter area of research is in its infancy, though of considerable importance for managing in the marine environment and for scientific issues concerning the carbon cycle.

The assimilation of satellite and ground-based data for the land surface is important for improving important elements of ESMs: the surface energy balance (including surface temperature and surface albedo), and the coupled hydrological and carbon cycles involving surface vegetation. Methods have been developed to assimilate satellite data on soil temperature, soil moisture, snow/water equivalent, as well as on vegetation type and biomass. The heterogeneity of the land surface and the complexity of the processes – many of which are poorly known or poorly modelled – make this area of data assimilation highly challenging and, at present, comparatively rudimentary. Data assimilation in land-surface models is largely limited to treating vertical (height) columns independently. Moreover, satellite data are assimilated not directly as radiances but as derived products (such as leaf-area index) which may have only an indirect relation to the variables appearing in the governing equations of the models. Significant progress has, however, been made recently with the JULES model. The ingredients for a 4D-variational data assimilation system have been developed, namely its tangent linear and adjoint counterparts. In addition, so-called observation operators are being developed, which will allow the direct assimilation of satellite radiances.

Methods to assimilate measurements of the croyosphere (land and sea ice) are being considered, but have not yet been implemented in coupled ESMs, at least in the UK. For land ice, the long timescales for changes and the difficulty of modelling these changes mean that data assimilation has limited value at present. For sea-ice, which changes significantly on the seasonal timescale, and which affects other components of the Earth system on this timescale, the development of data assimilation for sea-ice in a coupled climate system is an important area for future research.

17.2 Issues

There are scientific, technical and skills-related issues that need to be overcome to realise the benefits of data assimilation with ESMs, in particular to help deliver the central facet of the NERC strategy, viz. to improve climate forecasts on regional space and on seasonal to decadal time scales.

Key challenges scientifically are to develop methods (a) to accommodate nonlinearity in Earth system processes, (b) to represent the generally non-Gaussian nature of model errors, and (c) to deal with the coupled nature of the problem. Lack of knowledge of model errors, especially biases, is a serious impediment in data assimilation. Data assimilation should therefore be regarded as an iterative process, whereby the assimilation can be improved first by estimating model errors approximately, and then by improving these error estimates in the light of data assimilation experiments.

The technical challenges are also considerable, and include the complexity of algorithm design and optimisation, the formulation of tangent and adjoint models for variational assimilation and the difficulty of writing adaptable computer code. The heterogeneity of observations and the differing nature of their error structures must also be handled, a challenge of growing importance with the rapid growth and diversity of observational data from satellites. Progress would be expedited significantly if the research community had access to assimilation systems used operationally, and if they had advice and support on how to use them.

One of the greatest challenges is to remedy the serious shortage of skills in the UK needed to exploit data assimilation at the highest level. Only during the last decade has the use of data assimilation extended significantly from the operational community to the academic community. There is an urgent need for training in this discipline at postdoctoral and PhD levels.

17.3 International Context

The international competitiveness of data assimilation research and development with ESMs in the UK is not uniform. Implementations in operational weather and ocean forecasting at the Met Office are world class, though the sophistication of algorithms is significantly constrained by practicability. In the academic community, there are pockets of excellence in atmospheric and ocean science – derived largely but not exclusively from access to operational codes. In this respect, the adoption in the UK of a “Unified Model” with common computer codes for weather and climate forecasting is a great strength. Although in the land surface area the UK lags behind some other countries such as the USA and France, recent years have seen encouraging progress in catching up. The National Centre for Earth Observation has data assimilation as a pervasive component of its National Capability, and is promoting and accelerating the use in the UK of data assimilation with ESMs.

17.4 Strategy

17.4.1 Medium term strategy

Immediate goals to exploit data assimilation in Earth system modelling should include:

- To integrate fully the development of data assimilation algorithms with those of ESMs in a unified, adaptable structure that can accommodate diverse users and exploit readily advances made by different groups.

- To make advanced data assimilation codes for ESMs available to the research community with the support and expert advice needed to use and develop them effectively.
- To provide advanced training in the use of data assimilation in Earth system modelling.
- To undertake a concerted programme to test (coupled) climate prediction models stringently in "hindcast mode", by using data assimilation to initialise and then evaluate forecasts with satellite and ground-based observations.

17.4.2 Long term vision

The overarching goal is to lead advances in data assimilation methods to exploit the large international investment in Earth observing systems, notably integrated and sustained satellite systems such as the GMES system (Global Monitoring for the Environment and Security) being deployed by the European Space Agency in partnership with the European Commission. Allied to advances in high-resolution Earth system modelling, such capability would form the foundation of an "Earth Management System" with wide-ranging scientific, economic and geopolitical benefits for the UK.

17.5 Interfaces

The scientific interface to Earth system modelling will be driven by the need to evaluate ESMs in forecast mode, facilitated by using observations to initialise forecasts and observations to evaluate them. This scientific imperative, at the core of the NERC strategy, demands that data assimilation modules must be considered as an essential component of ESMs and developed in a fully integrated fashion with them.

17.6 Implementation Pathway

To achieve the medium- and long-term goals set out above, close collaboration between the operational and academic communities is vital, since the scientific, technical and resource requirements are highly challenging. The JWCRP provides the means to co-ordinate this effort and to seek resources for it. The NCEO has data assimilation as an integral part of its National Capability, and seeks to pioneer the academic contribution by collaboration with other NERC centres such as NCAS within the JWCRP and through international collaboration funded by international research and development programmes.

18.DATA - SUPPORT FOR EARTH SYSTEM MODELLING OUTPUT

Recommendation 18: NERC should consider developing an integrated national modelling output facility within its data centre infrastructure.

18.1 Current Capability

Earth System Models produce huge volumes of data. Data production is generally rapidly followed by interim archival, before subsequent analysis (including visualisation and/or numerical processing). Some simulations are suitable for long-term archival (see criteria at http://badc.nerc.ac.uk/data/BADC_Model_Data_Policy.pdf).

MOHC data products are seen as being the standard for others to aspire to, albeit often with access conditions which limit access. Alongside the MOHC itself, many key MOHC model products are available via the NCAS British Atmospheric Data Centre (BADC). Many model products from the NERC community are also available from the BADC, but other institutions also host product archives as well. In general the costs of model archival are born by the programmes which generate the data.

Visualisation tools are developed in a range of institutions with a range of capabilities.

18.2 Issues

Analysis ought to be followed by a decision as to whether to discard some or all of the data (e.g. the simulation did not have enough fidelity to address the problem at hand, or not all output is relevant to analysis), or to keep some or all of the data for further analysis (or as evidence underpinning conclusions). Without a process to ensure such proactive decision making storing model output data can be unproductive and unnecessarily expensive.

ESM simulations are carried out in a range of locations, and there is no common analysis facility in the UK. Individuals generally carry out analysis by moving data primarily to local computing system. With the advent of an ever wider range of computing platforms on which earth system models are run, ensemble processing and inter-model comparison will become difficult without infrastructure to facilitate both finding and manipulating simulation output.

High spatial and temporal resolution data is difficult to visualise, as is heterogeneous data from different computational systems (and diverse grid systems). Resources need to continue to be invested for both simulation documentation and establishing data standards to facilitate comparison and visualisation. Because much scientific analysis needs to be carried out on native grids, it is likely that multiple end-user diagnostic and visualisation packages will be needed. Most such packages are currently not parallelised in any way, and this will become a limiting factor for large analysis tasks.

18.3 International Context

The NERC Data Centre network has an international reputation in the management and dissemination of science data including model output data.

Most large modelling groups host their own product archives, however, most such data is inaccessible outside the originating centre. However, in the context of large modelling intercomparison experiments, and in the context of the IPCC, model output archives exist. The two most prominent such archives are the "MIP" (Model Intercomparison Archives) archives at the Lawrence Livermore Laboratory Programme for Climate Diagnosis and Intercomparison (PCMDI) centre, and that of the IPCC Data Distribution Centre. The latter is led by the BADC, who together with the World Data Centre for Climate (hosted by the German Climate Computing Centre, DKRZ), host the bulk of the IPCC data. For the forthcoming fifth climate model intercomparison project and IPCC assessment reports, PCMDI, DKRZ and BADC are jointly managing the data under the auspices of the "Earth System Grid Federation". Within Europe, BADC is working in the context of the European Network for Earth Simulation on a number of projects, primarily with European Commission funding, to expedite the availability and use of European earth system model output.

NCAS (mainly, but not exclusively through the BADC) currently supports, in partnership with PCMDI and the US NOAA, the Climate-Forecast (CF) conventions for NetCDF. CF is, and will continue to be, an important component of the ecosystem of software and standards for managing ESM output.

18.4 Strategy

18.4.1 Next 5 years

The NERC Science Information Strategy (SIS) provides a clear vision that NERC will work with its communities to deliver the data and information needed in support of the NERC strategy „Next Generation Science for Planet Earth‟. The headline activities of the science information strategy include:

- Supporting researchers in the location and evaluation of the data to maximise its re-use and re-purpose;
- Providing better facilities to manage and interpret increased data heterogeneity and volume;
- Equipping information scientists and scientists with key skills to work with the large scale data that the proposed science requires;
- Providing the informatics tools and techniques to support the development of integrated research communities;
- Working with discipline-based and cross-disciplinary bodies, both nationally and internationally, to influence the development and adoption of information science and technology standards.

Some of the issues outlined above will be addressed by the SIS implementation activity under these headings, but many, particularly those associated with grids and complex visualisation, will remain in the research and support agendas of most of the NERC centres - to be addressed with all modes of funding. Existing support for CF should continue, and extra support for CF conventions (as well as standard names) should be provided.

18.4.2 10 year horizon

In the longer term NERC should consider setting up a specific modelling output facility, where data which has passed the initial analysis phase can be accumulated (from wherever it was generated) to facilitate model-model and model-data comparison. Ideally this would be co-located with high volume earth observation data archives. This could be co-located with a small computational system for analysis and visualisation, which could additionally provide a “private cloud” to allow users to develop their own software solutions on virtual machines and deploy them alongside the data. Such a facility could then take part in a coordinated European approach to handling and exploiting ESM output.

The existing heterogeneity of software for manipulating ESM data should bifurcate into support for common (at the European scale) software libraries for handling data, and heterogeneous software for analysis and complex visualisation built upon those libraries (with the latter, as now, developed and funded within research groups). Simple visualisation systems should be developed and maintained within the data centre network.

18.5 Implementation Pathway

Earth System Model simulations which produce high volumes of data carried out with NERC funding should continue to be archived at one of the NERC dedicated data centres (most probably BADC), who should be tasked to ensure that appropriate software systems to manage the data are developed and implemented.

In the medium term, a new capacity is needed as outlined in the 10 year horizon above. The major technical milestones in developing such capacity include: a) deciding on an appropriate capital spend per annum (which we would then expect to correspond to increasing data storage year on year), b) establishing the overheads costs of this expansion, and c) recruiting staff to run the analysis systems (major tasks would be system management and application installation – but the latter would be minimised if the private cloud approach was used). These steps could be carried out within a year, and could build on a concept currently under discussion to deliver a widely accessible archive of data from MONSOON.

It would also be important to establish some community governance of what is archived, and what software is needed – both to manage the data and for visualisation and analysis. The existing criteria for what should be archived would need to be updated, and actively managed. Software systems which can manipulate complex gridded datasets will continue to need development and maintenance, and this work should be enhanced (and continue to be led by NCAS-CMS)., Coordination of data analysis software development within the UK and Europe should be also be within scope of this enhanced effort. Extra support for CF convention changes within NCAS-CMS would allow more timely changes to the CF conventions, removing a burden of data rewriting from the scientific community.

19.OTHER ISSUES

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.

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.

19.1 Education, Training and Career Development

19.1.1 Current Capability

There are relatively few young scientists who work in this field, largely because there is no straightforward path toward it. Current working scientists have typically wandered in from related fields. The lack of a directed educational path leaves the field in a shadow to students who must choose to focus their efforts at an increasingly early age. The reason for the field‟s lack of visibility is probably related to its holistic nature: it typically requires a broad range of knowledge including physical, chemical, and biological aspects of land-surface, oceanographic, and atmospheric realms, plus a high-level of numeracy.

19.1.2 Issues

Earth system models will become increasingly important as global problems of both climate change and population growth (hence pressure on a wide range of resources) magnify over the next few decades. If the UK is to maintain leadership or at the very least have a significant voice in the scientific debate and resolution of these issues, we must seriously undertake an overhaul of the route through the educational system and into this scientific field. This is a long-term goal which will require a tenacious and consistent effort on the part of the community in its engagement of government bodies. NERC can and should lead this process. In the short-term, however, there remains the issue that the current career path in the University system (or funding mechanisms) does not attract the best people, or does not allow otherwise successful people to be retained in their positions.

19.1.3 Strategy

The long-term strategy must be to develop alternative models of both career paths and educational programmes (from school through university) that attract and retain talented scientists. The short-term strategy must be to develop a certified training programme (not unlike the present software certification programs developed by Oracle, Sun Systems, etc.), aimed at both undergraduate and postgraduate levels of education.

19.1.4 Implementation Pathway

Implementation of the long-term strategy should start with a community-led effort to both document the capabilities and needs of the ESM field, and to develop straw-man alternatives to resolve the issues. The short-term implementation route requires the setting up of a dedicated ESM Training School and a curriculum that steps through a series of qualifying certificates, hosted by a consortium of relevant institutes.

19.2 High Performance Computing

19.2.1 Current Capability

NERC provides community access to a diverse range of HPC capability. At the top end (Tier 1) are national supercomputers. These are currently HECToR (RCUK service managed by EPSRC) and MONSooN (joint service with, and managed by, the Met Office). Local services (Tier 2) funded by NERC include mid-range clusters. Additionally, NERC also supports access to other Tier 2 services at universities.

NCAS provides centralised support for models, data and tools, for the majority of the NERC ESM community. It offers advice and help in using and optimising the models on HECToR and provides access to MONSooN. Other support from NERC Centres and universities is variable.

19.2.2 Issues

Increased investment in HPC infrastructure is necessary if the UK is to remain internationally competitive in the research supported by HPC. While future research challenges requiring increased HPC capability can be identified, it is more difficult to define and quantify the capability required and prepare a business case for additional investment. Affordability at an organisational or national level is becoming a real issue.

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. It will be a major challenge to exploit this next generation hardware. For example, the „dynamical cores‟ of climate and weather models that have been developed to simulate the atmosphere on today‟s computers, will not be able to exploit the available processing power.

19.2.3 Strategy

NERC has recently completed a strategic review of HPC. Some of the main conclusions of the review that are relevant to Earth System Modelling are that NERC should:

- plan for a growth in demand for HPC and for access to more powerful supercomputers in partnership with others;
- provide access to „future‟ machines to maximise the value of the current suite of application codes through porting and testing on next-generation architecture;
- develop a HPC roadmap to inform code development.

NERC and the Met Office are 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.

19.2.4 Implementation Pathway

The HPC roadmap will be developed by NERC in the coming months. Involvement of the ESM science community will be through representation on the NERC HPC Steering Committee.

19.3 Grid and Cloud Computing

ESM development also needs to be cognisant of ongoing developments in Grid and Cloud computing. Distributing a single high-resolution climate model over the Grid is likely to remain ineffective for the foreseeable future because of latency and band-width issues, but Grid and Cloud computing represent a low-cost and low-environmental-impact alternative to HPC for experiments such as the large ensembles necessary for risk analysis and the complication 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 more efficient models that can be run on Grid or other distributed architectures.

Annex 2

The ESM Strategy Group

NAME	ROLE	DECLARED MODEL INTERESTS
Martin Visbeck (Chair)	Kiel, Physical Oceanographer	
Icarus Allen (PML)	Marine ecosystem modeller	ERSEM regional downscaling, shelf seas, coupled with NEMO
Myles Allen (University of Oxford)	climateprediction.net	HADCM3 models, large ensemble forecast
Olivier Boucher (Met Office)	Climate, chemical, ecosytem modelling	HADGEM, JULES
Mike Ellis (BGS)	Geology, climate change modeller but not global	Terrestrial response models, linked to impacts
Jonathan Gregory (Reading)	NCAS Climate, Met Office Fellow – Hadley Centre	QESM, FAMOUS
Richard Harding (CEH)	Land based biogeochemical and hydrological modelling	JULES, other biogeochemical and hydrological models
Jason Holt (NOCL)	Ocean modelling, particularly shelf seas	POLCOMS, ERSEM, developing coastal version of NEMO
Tim Jickells (Earth System Science Theme Leader)		
Bryan Lawrence (NCAS)	BADC with interests in models outputs, data inputs, catalogues	Broad interest in all models
Hedong Liu (NOCL)	Ocean modeller	NEMO, ICOM European shelf seas
Stephen Mobbs (NCAS)	Director of NCAS	UM in all forms, developing QUEST-ESM, NCAS services to access UM, other models for chemistry and weather systems
Adrian New (NOCS)	Ocean modelling	NEMO, ICOM, MEDUSA
Alan O"Neill (NCEO)	Director of NCEO	UM and subcomponents thereof
Tony Payne (Bristol)	Ice sheet modelling	GLIMMER-CISM ice-sheet model, GENIE

Colin Prentice (Grantham Institute for Climate Change and Division of Biology, Imperial College)	Leader QUEST	QESM and subcomponents thereof
John Pyle (Cambridge)	Atmosperic chemistry, UKCA	UKCA, GLOMAP
Paul Valdes (Bristol/NCAG)	NCAG. Paleoclimate	Model omnivore – uses at least half of the models under consideration, GENIE – lead PI, FAMOUS etc
Eric Wolff (BAS)	Polar science and paleoclimate	Not modeller, works on ice cores
Richard Wood (Climate System Theme Leader)	Met Office	UM, with main interest in ocean model components
IN ATTENDANCE		
Zof Stott (Assimila)		
Jon Styles (Assimila)		
Rachel Capon (Assimila associate)	Note taker (Meeting 1)	
Ned Garnett (Swindon Office)	Science and Innovation Manager, atmosphere and polar	
Andy Parsons (Swindon Office)	JWCRP programme manager, (shared NERC-MetO), was NERC HPC manager	
Dominique Balharry (Swindon Office)		

Annex 3

Terms of Reference for the Strategy Advisory Group[3]

Introduction

The convening of this strategy advisory group directly relates to delivery of the NERC Strategy, in particular Science Themes Climate Systems and Earth System Science. More information about the themes and action plans arising from them is available on the NERC website .

NERC wishes to develop a National Strategy for Earth System Modelling. This will provide a strategic framework for the long-term support and development of these highly complex models to secure existing capability, ensure effective coordination of activities at a national level, and embrace new developments. Earth System Modelling (ESM) is central to predicting climate and environmental change, critically important for extrapolating observational data to broader space and time scales, and to exploring linkages and feedbacks within the Earth System.

Collaboration with the Met Office Hadley Centre is a key part of NERC"s strategy for Earth System Modelling. A Joint Weather and Climate Research Programme has been established with the Met Office with the aim of ensuring that: „the UK maintains and strengthens its leading international position in climate science and hence in climate forecasting and the provision of advice for climate policy". The work in developing the national strategy for Earth System Modelling will therefore need to be closely aligned with the work of the JWCRP.

In addition a further joint action is planned with the Met Office as part of the JWCRP on „Next generation modelling for weather and climate prediction". This will aim to undertake a scoping study to determine how the UK"s unified model will need to develop over the next 5 – 10 years to:

exploit the rapid advances in high performance computing;

better represent the multi-scale nature of weather and climate processes;

make more effective use of observational data, particularly data assimilation.

However, NERC"s strategic requirement for Earth System Modelling is broader than climate modelling and encompasses the use of software not used or supported by the Met Office.

Terms of Reference

The strategy advisory group will:

Assess the current status of UK ESM capability, relative to international benchmarks e.g. science quality, usability for research purposes and scalability

Assess the ESM needs for NERC over the period of the current strategy (2008-2013) and beyond e.g. what processes will need to be simulated, at what resolution, timescale and level of complexity? Should NERC aim to focus on a fewer number of models or work towards an engineered diversity?

Prioritise the ESM needs, taking into account science and policy drivers, current investment, opportunities for impact in an international context and cost effectiveness

Propose appropriate training requirements to deliver the ESM needs over the period of the current NERC strategy and beyond

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[3] This Annex reproduces NERC"s original Terms of Reference. In practice the ESM Strategy Group concentrated on "Strategy", rather than a detailed "Implementation Plan". It was felt that detailed issues of funding and implementation were best considered elsewhere. The group also concentrated on NERC"s potential contribution to a National Strategy, rather than a National Strategy in its totality. Further consultation with other stakeholders, particularly the Met Office/Hadley Centre will be required before an overall National Strategy can be developed and agreed.

Propose a clear approach to evaluating model performance e.g. issues of validation and benchmarking

Propose mechanisms for delivery of the ESM needs, looking for cost effective solutions to meet the needs e.g. considering different funding streams and potential for reciprocal agreements between NERC and other organisations

Identify and select a sub-set of ESM activities that would benefit NERC to support as National Capability, and propose a clear plan for their development

Propose mechanisms for effective coordination of ESM activity between NERC and the Met Office

Propose mechanisms for refreshing of the ESM strategy and interactions with other relevant strategies e.g. the NERC HPC strategy

Consolidate the views of the ESM community into the strategy and implementation plan following a consultation

Mode of Working

The group will develop the draft strategy and implementation plan at a 2-day meeting (5-6 October 2009). The documents will be published for consultation with the ESM community and their view consolidated and included in the strategy and implementation plan by the strategy group at a 1-day meeting (7/8 December 2009 tbc).

Inputs

Inputs to inform the working of the strategy advisory group include:

Audit of UK ESM capability, relative to international benchmarks and assessed against NERC"s strategic priorities

Information on NERC strategic themes and feedback from the theme leaders on what they see as the potential future requirements for ESM

Meeting report from the QUEST Scientific Liaison Group meeting on a UK strategy for ocean biogeochemical modelling

Information on the NERC Met Office Joint Weather and Climate Research Programme

NERC HPC strategy

Outputs

The output of the strategy group will be a National Strategy and Implementation Plan for Earth System Modelling. The customers for this strategy are the NERC Directors of Strategy and Partnership and Science Delivery.

The strategy and implementation plan will be presented to the National Capability Advisory Group in early 2010 for approval.

Membership

The strategy group will be appointed by NERC and comprise members of the research community with experience in the development and use of Earth System models.