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Key outcomes/non technical summary

There is an increasing recognition of the importance of Earth system components and feedbacks in the climate system. As a result, we have assessed the scientific requirements of the next generation Earth System model to be developed by the Hadley Centre, namely, HadGEM3-ES. In particular, we have considered replacements and/or upgrades to the existing Earth system components in HadGEM2-ES as well as additional new components. The existing components include the carbon cycle, terrestrial vegetation, ocean biology, and atmospheric chemistry. New potential components include land ice, waves, biophysical and biogeochemical impacts. We have assessed the various options currently available or expected to be available from the Hadlley Centre as well as the wider academic community within the HadGEM3-ES development timescale (i.e. 2012-2015) and made a number of recommendations. Given the complexity of developing HadGEM3-ES, we have also provided suitable "fallback" positions.

Associated publications

None

Press interest

None

Scoping for HadGEM3-ES

1. New Scientific Questions for HadGEM3-ES

The new science that is expected to be carried out with HadGEM3-ES fits within 3 broad areas as follows:

Biogeochemical cycles and feedbacks

- Improved representation of vegetation including fires
- Nitrogen cycle
- Ocean biogeochemistry
- Improved indirect radiative forcing from aerosols
- Seamless prediction of ozone through the troposphere and stratosphere
- Enhanced coupling between surface/vegetation schemes and chemistry (e.g. biogenic emissions, fire emissions, ozone damage)

Role of land use and short-lived atmospheric species on decadal timescales

- Improved aerosols and chemistry

Impacts of climate change on ecosystems, water resources, and society

- Land-use change and fires
- Irrigation, inundation, and wetlands
- Permafrost degradation/thaw
- Impact of ozone on vegetation
- Changes in ocean ecosystems and ocean acidification
- Fate of ice sheets and their role in future sea level rise

Some of this new science is driven by clear scientific drivers (e.g. role of nitrogen cycle in carbon cycle feedbacks, role of troposphere-stratosphere chemistry) while some is being proposed to assess the impact of new interactions (e.g. land-biosphere-chemistry interactions) resulting from the proposed enhanced capability of HadGEM3-ES.

The applications of HadGEM3-ES could be far reaching. For example, the model could be used for centennial timescale projections of climate change, as was for the case for HadGEM1 and HadGEM2-ES. However, at higher resolution, it could also be used for predictions on a decadal timescale. Likewise, a lower resolution version of the HadGEM3-ES model could be used to explore uncertainties associated with emission pathways, feedbacks, and model parameters.

2. Project Objectives

1. To build a new Earth System model, using as the physical basis the atmosphere-ocean coupled model, HadGEM3-AO.
2. To provide an Earth System model capable of delivering new science relevant to DECC, Defra, and other customers.
3. To incorporate science developments, updates, and model fixes from HadGEM3-AO within the HadGEM3-ES development timescale.

3. Recommendations

In order to meet the objectives outlined in Section 2, the following recommendations are made:

- It is recommended to have a project board (PB) to agree the project objectives, to periodically review progress, and to ensure that adequate resources are in place to enable the project's objectives to be met. The project should start in early 2012, with a development timescale of 4 years.

- The decision to extend the lifetime of the IBM or procure a new supercomputer underpins key decisions in HadGEM3-ES (e.g. resolution, complexity). Therefore, it is essential that a decision on MO supercomputing capability over the 2012-2015 timescale is made as soon as is feasible and communicated to the HadGEM3-ES PB.

- If a new supercomputer is to be procured within the HadGEM3-ES timescale, its timing will have an important impact on the success of HadGEM3-ES. In particular, having user access later than September 2014 represents a significant risk to having a completed model running on the new supercomputer by late 2015.

- If a new supercomputer is to be procured within the HadGEM3-ES timescale, it is recommended that a HadGEM3-ES prototype be available in sufficient time to form part of the procurement benchmarking exercise.

- HadGEM3-AO is currently available at two resolutions: N96L85-ORCA1.0L75 and N216L85-ORCA0.25L75, with significant scientific benefits at high resolution. However, the only feasible resolution for HadGEM3-ES, based on current computational costs, is a configuration with an atmosphere and/or ocean of intermediate resolution (N144, ORCA0.5). A decision on the choice of resolution should be made by early 2013.

- The lower resolution N96L85-ORCA1.0L75 version of HadGEM3-AO should be used for early HadGEM3-ES development and for doing sensitivity tests and/or ensemble runs.

- Optimisation is essential to the success of HadGEM3-ES and underpins key decisions on model resolution and complexity and will determine the model throughput. Therefore, it is critical that optimisation becomes an integral part of the HadGEM3-ES development project plan.

- With the proposed complexity of HadGEM3-ES and the high degree of external dependencies, it is particularly critical to the success of HadGEM3-ES to have a project manager and a dedicated configuration manager for the duration of the project. The success of HadGEM3-ES will also be dependent on how the MO-NERC collaboration strategy evolves.

- It is recommended that the HadGEM3-ES project plan includes a clear strategy on evaluation of the model, assessment of new interactions, as well as on effective and timely spin up of the various ES components.

- The recommended models for dynamic vegetation, the terrestrial carbon and nitrogen cycles and fires are ED-SPITFIRE-ECOSSE-FUN, with priority being given to ED and the nitrogen cycle. A decision on the suitability of these ES components should be made by end 2012.

- A comprehensive benchmarking exercise on the different OBGC models available is essential before any particular model can be recommended for inclusion in HadGEM3-ES. On the outcome of the OBGC benchmarking exercise and the computational cost of the models, a decision regarding the choice of OBGC model should be made by early 2013. This OBGC model should then be included in the HadGEM3-ES prototype by late 2013, in time for the benchmarking exercise which will form part of the new supercomputer procurement process.

- There are strong scientific drivers for the UKCA chemistry component of HadGEM3-ES to include an extended model top and a troposphere-stratosphere chemistry scheme, online photolysis, an improved treatment of wet and dry deposition, with enhanced interactions with the land surface and vegetation. Priority should be given to the chemistry, then photolysis, followed by wet and dry deposition. The choice of chemistry scheme and photolysis can be made in early 2012 and both should be implemented in a HadGEM3-ES prototype by late 2013, in time for the benchmarking exercise which will form part of the new supercomputer procurement process.

- The CLASSIC aerosol scheme in HadGEM2-ES and HadGEM3-AO should be replaced with UKCA-MODE, the aerosol component of UKCA. It should be running in the HadGEM3-ES prototype by late 2013.

- It is recommended that the expected improvements to the UM's dynamical core (scalability, SLICE) available in late 2012 from ENDGAME or its fallback position be adopted by the HadGEM3-A model before HadGEM3-ES.

- There are a number of scientific drivers (e.g. sea surface albedo, sea-air fluxes, sea salt emissions, and wave impacts) which make the inclusion of a wave model in HadGEM3-ES desirable. However, its inclusion in HadGEM3-ES is not essential for the success of the project.

- The inclusion in HadGEM3-ES of Greenland and Antarctic ice sheets using the Glimmer model as a switchable option is recommended. However, land ice is not essential for the success of HadGEM3-ES.

- It is recommended that both biophysical and biogeochemical impacts become an integral part of HadGEM3-ES. Although there are added benefits to having impacts included, they are not critical for the success of HadGEM3-ES.

- Given the complexity of developing an ESM, it is recommended that ES components are not viewed simply as "add-on" to the coupled atmosphere-ocean model but are viewed as an integral part of any future model development.

4. Project Background

Building on the Met Office Hadley Centre (MOHC)'s reputation for identifying and quantifying feedback mechanisms in the Earth System (e.g. Cox et al., 2000; Johnson et al., 2001; Gunson et al., 2006; Sitch et al., 2007), HadGEM2-ES was the Hadley Centre's first global Earth System model (ESM) which brought many of these feedbacks together in a single model. In particular, it includes:

- Land, atmospheric, and ocean carbon cycle
- Terrestrial vegetation
- Ocean biology
- Atmospheric chemistry
- New and improved aerosol species (e.g. fossil fuel organic carbon, dust, sulphate)
- New couplings (e.g. vegetation-carbon cycle)

The majority of planned runs with HadGEM2-ES for the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) have already been completed and the MOHC is well placed to exploit these runs. Initial analysis has already started and there are plans to co-ordinate the research effort to maximise the impact of MOHC science on the Intergovernmental Panel on Climate Change (IPCC)'s fifth assessment report (AR5).

However, despite the success of HadGEM2-ES to date and the potential from the IPCC AR5 integrations, some of the model components (e.g. dynamic vegetation, ocean biogeochemistry) have scientific limitations and on a timescale of 3-4 years, will no longer be suitable for the scientific questions that we will wish to address with an ESM. For example, the MOSES/TRIFFID land surface and vegetation model (Cox et al., 1999; Cox et al., 2000) doesn't include a nitrogen cycle, and could therefore be underestimating the reductions in carbon emissions required to achieve atmospheric carbon dioxide stabilisation at a given level (e.g. Thornton et al., 2007; Sokolov et al., 2008; Zaehle et al., 2010). Likewise, the representations of cell processes in the ocean biogeochemistry and ecosystem model, diat-HadOCC, are based on those of the HadOCC model (Palmer and Totterdell, 2001) which was developed nearly two decades ago. Since then, the scientific understanding of phytoplankton processes has increased and newer models take this improved understanding into account. The atmospheric chemistry component of HadGEM2-ES is a very simple tropospheric scheme from the United Kingdom Chemistry and Aerosol (UKCA) project. It models tropospheric ozone and methane reasonably well (O'Connor et al., In prep.) and provides online oxidants for sulphate aerosol production (Collins et al., In prep.). However, it excludes important processes such as the impact of climate change on the recovery of the stratospheric ozone hole (e.g. Waugh et al., 2009), the influence of stratospheric ozone on atmospheric dynamics and temperature (e.g. Shindell et al., 1999; Butchart et al., 2003), and the impact of climate change on future surface ozone concentrations through changes in vegetation and biogenic volatile organic compound (BVOC) emissions (e.g. Sanderson et al., 2003).

As a result, there is a recognised need to update and enhance the complexity of components in the next generation ESM in order to ensure that the MOHC maintains its world-leading capability in climate and Earth System modelling. Equally, according to the review on the role of the Hadley Centre in providing climate science advice to Government by Beddington et al. (2010), the MOHC cannot operate in isolation. It has a critical and co-dependent relationship with the UK climate science community, which is similarly world class. The Beddington et al. (2010) review acknowledges that there is significant advantage associated with working more closely with the academic community. Therefore, it is envisaged that the development of HadGEM3-ES will be co-ordinated by the MOHC but with significant model development and interpretation contributions from the wider academic community.

Over the past couple of years, there have been substantial improvements in the latest physical climate model, namely HadGEM3-AO. Therefore, for the MOHC's next ESM, the coupled atmosphere-ocean model HadGEM3-AO will form the physical basis. The replacement of MOSES II (Essery et al., 2003) with the Joint UK Land Environment Simulator (JULES) model in HadGEM3-AO has recently taken place. Therefore, for HadGEM3-ES, it is appropriate to make use of model developments from the wider academic community which have been coupled to JULES and are relevant for modelling vegetation dynamics, terrestrial carbon and nitrogen cycles, and fires on a global scale. These developments will be discussed further in Section 6.

In addition, the physical model HadGEM3-AO has adopted NEMO (Nucleus for European Modelling of the Ocean) as its ocean component. Therefore for HadGEM3-ES, it seems both timely and highly appropriate to make use of model developments from the wider academic community which have been coupled to NEMO and are relevant for modelling ocean biogeochemistry and ecosystems. These developments will be discussed further in Section 7.

Furthermore, UKCA is an ongoing collaborative project between the MOHC and NCAS/NERC partners and model development has progressed significantly since UKCA was first implemented in HadGEM2-ES. Therefore, there is considerable potential to enhance UKCA capability in HadGEM3-ES and this will be discussed further in Section 8.

In addition to enhancements to and/or replacement of the Earth System components beyond those of HadGEM2-ES that are considered critical to the success of HadGEM3-ES, there is also the opportunity to add new less critical components. For example, the coupling of ice sheet models to climate models is of importance for projections of the fate of ice sheets under future climate change and their influence on the hydrological cycle and future sea level rise. The inclusion of a wave model would have implications for sea surface albedo, sea-air fluxes of carbon dioxide (CO_2) and dimethyl sulphide (DMS), sea salt emissions, and impacts such as ship routing, coastal defences, oil rig structures, wave energy generators etc. Furthermore, there are two main drivers for having impacts as an integral part of the HadGEM3-AO/HadGEM3-ES models. Firstly, it avoids the transfer and post-processing of very large quantities of data to drive offline impact models. By having impacts as a direct output from climate simulations, it means impact studies can take advantage of more scenario-driven simulations and ensembles. Secondly, some of the impacts themselves (e.g. glacial melt) may have a significant impact on regional climate.

Developments in relation to modelling land ice, waves, and impacts are ongoing and HadGEM3-ES could take advantage of these developments although their inclusion is not crucial to the success of the ESM. These model developments will be discussed in more detail in Sections 9-11.

Below, in Section 5, we consider the current status of the atmosphere-ocean coupled model, HadGEM3-AO, and each of the Earth System model components being considered for inclusion in HadGEM3-ES (Sections 6-11).

5. HadGEM3-AO

The HadGEM3-AO model is currently being developed under the CAPTIVATE (http://collab.metoffice.gov.uk/twiki/bin/view/Project/CAPTIVATE/WebHome) project. The two configurations are N96L85-ORCA1.0L75 and N216L85-ORCA0.25L75, with the high-resolution configuration offering significant advantages over its low-resolution counterpart in terms of the representation of the El Niño Southern Oscillation (ENSO), reduced mean biases in the North Atlantic, and teleconnections in Africa related to ENSO. However, the cost of N216L85-ORCA0.25L75 is ~10 times that of N96L85-ORCA1.0L75, making it unfeasible as the basis model for HadGEM3-ES (see Section 12 on High Performance Computing). N96L85-ORCA1.0L75, on the other hand, does not provide any scientific benefits over HadGEM2-ES in terms of horizontal resolution. There could be some advantage to having a version of HadGEM3-AO at an intermediate resolution for HadGEM3-ES (e.g. N144L85-ORCA0.5L75, N96L85-ORCA0.25L75) although the N96L85-ORCA1.0L75 version should be used for early HadGEM3-ES development, sensitivity tests, and/or ensemble runs. The feasibility of using HadGEM3-AO at an intermediate resolution for HadGEM3-ES will be discussed further in terms of computational cost and will depend on the supercomputer procurement; a decision on resolution ought to be made no later than early 2013.

There is a possibility that HadGEM3-AO will never be frozen but will continually be developed like the MO operational models. There will be standard versions available, including one specifically for HadGEM3-ES development from late 2011. If this is the case and the development timescale for HadGEM3-ES is 2012-2015, it is likely that the physical model used by HadGEM3-ES will need to be updated to keep it in line with HadGEM3-AO. For the purpose of having some stability for HadGEM3-ES development, it is envisaged that this update (including a possible change in resolution) will be carried out twice. The first upgrade from HadGEM3-AO to HadGEM3-ES should include the change in resolution, so that the HadGEM3-ES prototype is based on the resolution to be used for the final HadGEM3-ES configuration. It is recognised that the change in resolution could represent a significant effort, both technically and scientifically, for the Earth System components.

Given the complexity of developing an ESM and the scientific importance of the Earth System components themselves, there would be a number of advantages in the future if ES components were not considered as “add-ons” to a coupled atmosphere-ocean model but were viewed as an integral part of the model itself. In particular, this approach would avoid a two-stage development process such as has been the case with HadGEM2-AO/HadGEM2-ES and will be the case for HadGEM3-AO/HadGEM3-ES. More importantly, it would enable model assessment to be carried out in a more integrated way i.e. assessing impact of ES component on model performance as well as evaluating the behaviour of the component itself. Finally, it would help to avoid problems in model behaviour which has implications for the performance of ES components e.g. summer dry bias in HadGEM2 and impact on vegetation. Therefore, for model development projects beyond HadGEM3-ES, it is recommended that ES component development is carried out alongside other model developments.

The Dynamics Research group is currently testing a replacement dynamical core, called ENDGame (Even Newer Dynamics for General Atmospheric Modelling of the Environment). It could be more stable, more scalable, with a better effective resolution than New Dynamics (ND) and the aim is to keep the increase in cost of the dynamical core to within a factor of 2. A decision on whether to adopt ENDGame in the operational models will be made in the next few months. There are also plans to have a Semi-Lagrangian Inherently Conservative and Efficient (SLICE) algorithm (Zerroukat et al., 2005; 2008) as an option to ENDGame in order to conserve tracers both globally and locally, thus addressing some tracer transport problems seen in HadGEM2-ES.

If ENDGame is not adopted, then there are plans within Met R&D to retrofit the best aspects of ENDGame (i.e. SLICE and scalability) to ND on a timescale similar to ENDGame i.e. late 2012. Either way, there will be improvements to the UM's dynamical core and these should be adopted by HadGEM3-A before being implemented in HadGEM3-ES. If a supercomputer procurement is going ahead at the earliest possible time, then the latest that ENDGAME can be made available is end 2012, thus ensuring that it is implemented in HadGEM3-A by March/April 2013 and in HadGEM3-ES by July/August 2013. Additional work will need to be carried out to make certain Earth system components (e.g. UKCA) compatible with the change to the grid staggering. Glenn Greed from the UM Systems Team will co-ordinate efforts to ensure that the appropriate work on the various UM components gets done to accommodate the grid change following the release of UM7.8. However, extra effort may also be required for components which are currently not part of the UM, and which will be built in as part of the HadGEM3-ES development.

6. Terrestrial Carbon and Nitrogen Cycles and Dynamic Vegetation

The land surface and vegetation model components designed to be coupled to JULES include:

- **ED** ("Ecosystem Demography" model; Moorcroft et al., 2001) which accounts for several age classes and plant succession, and whose model parameters are more closely aligned with quantities readily observable in the field (R. Fisher et al., 2010)
- **SPITFIRE** which models fire activity, fire-induced vegetation mortality, and emissions from biomass burning (Thonicke et al., 2010)
- **ECOSSE** which simulates the coupling between soil nitrogen and carbon cycles (Smith et al., 2010a; Smith et al., 2010b)
- **FUN** which simulates nitrogen uptake and utilisation by vegetation, allowing CO_2 fertilisation of photosynthesis to be nitrogen-limited (J. Fisher et al., 2010)

A Joint Weather Climate Research Programme (JWCRP) position has been funded at Exeter University to comprehensively benchmark the JULES-ED-SPITFIRE-ECOSSE-FUN (JESEF) offline model, with a view to improving model performance and constraining various model parameters. The individual model components will also be coupled to the version of JULES in HadGEM3-A and the fully-coupled model will then be assessed using HadGEM3 metrics. The individual components themselves will also be evaluated on a global scale using new metrics such as leaf area index, biomass and soil carbon, CO_2 fluxes, fire frequency etc. and using a standard suite of land benchmarking tests which will be available in the next 2-3 years through an international benchmarking activity called iLamb. This benchmarking suite will contain tests for the medium to long-term dynamics, i.e. plant drought response- rates of tree mortality, vegetation response to elevated CO_2. This work is due to start in early 2011 and a fully-coupled model is expected to be available by mid-2012. A decision on the suitability of JESEF for HadGEM3-ES will be made by end-2012. It would also be useful if each of the individual components of JESEF could be switched on/off so that their impact on model performance can be assessed on an individual basis; this should form part of the model evaluation strategy recommended as part of the project plan. Likewise, it would be beneficial if it was possible to have a version of ED which ran in equilibrium mode; the equivalent version of TRIFFID was used within HadGEM2-ES to spin up the vegetation and carbon pools.

Under the NERC Tropical Biomes in Transition Project (TROBIT), Phil Harris at CEH Wallingford is making significant progress in the coupling of JULES and ED, and ironing out various issues. This will support the work of the JWCRP PDRA at Exeter. There are also plans to add tropical forest PFTs and savanna PFTs and this work will be continued within the AMAZONICA project co-ordinated by Manuel Gloor in Leeds. CEH Wallingford is heavily involved in both projects.

There is also a European Union funded project, called EMBRACE, with a specific focus on terrestrial carbon and nitrogen cycles, the output from which may feed into the JESEF development. Of these components, priority will be given to both ED and the nitrogen cycle, with lower priority given to SPITFIRE. Suitable fallback positions are discussed further in Section 15.

Stephen Sitch and Lina Mercado are both taking up posts at Exeter University in June 2010 and there is a genuine interest in further developing collaboration between the university and the MOHC. In particular, projects can be designed which identify weaknesses in the land surface model, the university can then conduct the field/experiment work necessary, and then work can be carried out collaboratively on model implementation. In particular, Lina has plans to work on a phosphorous cycle – especially important for the tropical ecosystems, which could be made available within the HadGEM3-ES timescale. Stephen also plans to work on vegetation response to future high temperatures and drought (i.e. plant acclimation). There are also 2 posts funded under Greencycles II at Exeter University (PhD on nitrogen cycle, PDRA on coupling) which will again help to support the work of the JWCRP PDRA at Exeter.

Furthermore, Catherine Luke and Peter Cox at Exeter University have been working on the compost bomb – adding the thermal effects of decomposition into the model should not be too difficult.

There are also joint plans between the MOHC and the Centre for Hydrology at Wallingford to improve the physics within JULES for the representation of permafrost. The progress made will depend to some extent on the success of FP7 and/or NERC funding. However, it is recommended that the suitability of any progress relevant to permafrost can be made in early 2012. This aspect of JULES development is not critical to the success of HadGEM3-ES but would provide the added benefit of being able to assess the impact of climate change on permafrost degradation/thaw.

In terms of land management, crops will be incorporated as part of impacts modelling but there are no definite plans to incorporate managed forest plantations.

7. Ocean Biogeochemistry and Ecosystems

For ocean biogeochemistry and ecosystem modelling, there are a number of possibilities including:

- **PlankTOM 4/5/10 Models** – a series of models of varying complexity based on the French PISCES-T model, which represent ecosystem dynamics based on Plankton Functional Types or PFTs (Le Quéré et al., 2005; Vogt et al., 2010)
- **MEDUSA** (Model of Ecosystem Dynamics, carbon Utilisation, Sequestration and Acidification) – a model similar in structure to diat-HadOCC, but with more up-to-date paramerisations (Yool et al., 2010; Popova et al., 2010)
- **ERSEM** (European Regional Seas Ecosystem Model) - a mature PFT model that is similar in functionality to PlankTOM and applied to shelf seas but is also being applied to the global open ocean (Vichi et al., 2007a; Vichi et al., 2007b; Vichi and Masina, 2009).

Given the availability of different biogeochemistry and ecosystem models, the recommendation is to have the ability to run them side-by-side in the same version of NEMO. Then, using appropriate assessment criteria based on the science that the MOHC would like to do with HadGEM3-ES, the performance and computational cost of the different models will be assessed and a decision on which model to include in HadGEM3-ES will be made in early 2013. It is recognised, however, that a single model may not be the most suitable for addressing all the scientific questions raised. Hence, it may be appropriate to weight the assessment criteria according to the priority of the science questions to be addressed with HadGEM3-ES. Likewise, there may have to be a compromise between performance and computational cost.

An initial workshop is planned for early-mid 2011 to bring the UK OBGC community together. This workshop will mark the beginning of agreeing assessment criteria, and the design and timetable of the benchmarking exercise so that a decision on the OBGC component of HadGEM3-ES can be made in early 2013.

8. UKCA

As indicated, there is significant potential to enhance the capability of UKCA in HadGEM3-ES. The recommended enhancements include:

- A troposphere-stratosphere chemistry scheme
- UKCA-MODE, the aerosol component of UKCA
- Online photolysis
- Improved wet and dry deposition

However, there are a number of drawbacks with the Newton-Raphson (N-R) chemical solver (Wild and Prather, 2000) required to support a troposphere-stratosphere chemistry scheme, such as computational efficiency, memory use, and bit comparability across different PE configurations. The High Performance Computing (HPC) team at the Met Office have already started to address them, with the aim of having the solver fit for purpose by the start of HadGEM3-ES (early 2012). It is at this stage that a decision can also be made on the complexity of the troposphere-stratosphere chemistry scheme and the online photolysis scheme (Fast-j/Fast-jX) for HadGEM3-ES. A phase of implementation and assessment in HadGEM3-A will follow and it is envisaged that a troposphere-stratosphere chemistry scheme, online photolysis, and UKCA-MODE will all be implemented in the HadGEM3-ES prototype by August 2013.

The aerosol scheme in HadGEM2-ES was the CLASSIC scheme, where each aerosol component is modelled individually with fixed size distributions, whereas UKCA-MODE treats aerosols as internal mixtures, where the composition of the mixture varies interactively. Mass and aerosol number are both prognostic variables, such that any change in mass does not necessarily imply a change in aerosol number, as is the case in CLASSIC. A comparison of CLASSIC and MODE and their direct radiative forcing in HadGEM3-A (Johnson et al., 2010) found that UKCA-MODE outperforms CLASSIC in comparison with measured aerosol optical depth (AOD) and gives a similar direct radiative forcing per unit AOD as CLASSIC, thereby making it suitable for use in HadGEM3-ES. It would also be beneficial to have a version of UKCA-MODE which could run with offline oxidant fields, as was the case with CLASSIC, and would provide a relatively computationally efficient model for aerosol evaluation. Work is also well underway to take account of aerosol indirect effects from UKCA-MODE.

From the recommended enhancements to UKCA, priority will be given to the chemistry scheme itself and aerosols, followed by photolysis and then deposition.

9. WAVE Model

No wave model component was included in HadGEM2-ES. However, there are plans to couple WAVEWATCH III (Tolman, 1997; 1999; 2009) to the UM’s atmosphere, thereby making it feasible as a potential new component in HadGEM3-ES.

Within a 2-year timescale, the impact of the wave model on the atmosphere model and the performance of the wave model itself will have been assessed from a Numerical Weather Predication (NWP) perspective but it is less likely that this assessment will have been completed for the ocean model. Extra resources may be required to ensure that this assessment is fully completed, particularly if a decision on the wave model's suitability for HadGEM3-ES is to be made by mid-2013. However, the inclusion of the wave model in HadGEM3-ES isn't critical to the success of HadGEM3-ES and is being proposed here to take advantage of existing plans.

10. Land and Sea Ice

Developments to the sea ice modelling component of HadGEM3-AO, called CICE (Hunke and Lipscomb, 2004), will automatically feed into HadGEM3-ES through planned upgrades of the physical model.

No land ice component was included in HadGEM2-ES. The ice sheet model being considered for inclusion in HadGEM3-ES is the Glimmer model (Rutt et al., 2009). Its computational efficiency makes it highly appropriate for modelling ice sheet evolution over long time scales. The model itself has been verified against a range of established standards, is well structured and documented, and is being promoted as an open source, community model. There are plans within the MOHC to implement Glimmer as a switchable option in HadGEM3-AO for the Greenland and Antarctic Ice Sheets within the next 2-3 years, starting with Greenland, thus making the inclusion of ice sheets feasible within the HadGEM3-ES development timescale. It would be particularly useful if the land ice could be spun up reasonably well from offline simulations; this should form part of the spin up strategy being recommended as part of the HadGEM3-ES project plan. A decision regarding the suitability of Glimmer could be made by mid-2013. As is the case with the wave model, the inclusion of Glimmer is not critical to the success of HadGEM3-ES but is being considered as an added benefit due to ongoing development plans.

11. Impacts Modelling

A variety of model developments focussed on biophysical impacts can be easily coupled to HadGEM3 through JULES. These include the following:

- Irrigation
- Crops and cropland productivity
- Glacier melt
- River flow
- Urban Scheme

By late 2012, there are plans to have these impacts fully coupled to the version of JULES within HadGEM3-AO. Beyond 2012, the configuration could be extended to include biogeochemical impacts, taking account of new Earth System components such as ED, SPITFIRE, ECOSSE, and FUN. This will very much depend on the progress made at Exeter University through the JWCRP post in fully coupling these components to HadGEM3 and the resources available within the Met Office Hadley Centre to do the various impacts-related couplings required. Although there are strong scientific drivers for having impacts in HadGEM3-ES, their inclusion in the model is not essential for the success of the project.

12. High Performance Computing

There is a planned upgrade to the existing IBM system in late 2011, with an expected increase in capacity of a factor of 2-3. Scalability of the UM and the HadGEM3-AO configuration, in particular, may be a challenge.

Depending on financial resources, it is anticipated that another upgrade to the Met Office's supercomputer will take place between late 2014 and late 2016. This system upgrade wouldn't necessarily be an IBM but could potentially provide another factor of 2-3 in capacity. If this upgrade were to take place within the HadGEM3-ES development timescale, it would be beneficial to have a HadGEM3-ES prototype in 2013/2014 so that it can be included in the basket of models used for benchmarking purposes as part of the procurement process. However, the timing of this upgrade underpins key decisions in HadGEM3-ES such as model resolution, complexity, and model throughput. The earliest estimate for user access to the new supercomputer is September 2014 with the latest estimate being September 2016. If HadGEM3-ES is to be completed by end 2015, then the availability of the new supercomputer and the effort required to get HadGEM3-ES ported, optimised, and scientifically assessed, represents a significant risk to meeting this target. The feasibility of this upgrade could be clearer when HPC requirements are reviewed again in 2012, following a recommendation from the Beddington et al. (2010) review.

One alternative possibility is to extend the lifetime of the upgraded IBM to beyond the timescale of completion of HadGEM3-ES. This would remove the necessity to port HadGEM3-ES onto a new supercomputer but would imply a reduction in capacity of 2-3 from that anticipated with the second upgrade.

Another alternative for HadGEM3-ES is the exploitation of European supercomputing capability. However, there would be a significant porting effort to make use of this capability.

It is recommended that a decision regarding the use of European supercomputing and/or timing of the supercomputer upgrade be taken as soon as is feasible.

13. Estimated HadGEM3-ES Model Cost

The estimated cost of the Earth System components in HadGEM3-ES relative to the atmosphere or ocean components is listed in Tables 1 and 2.

Component	Cost relative to HadGEM3-A
UKCA Chemistry (81/108)	+ 170%/290% (depending on choice of trop-strat chemistry scheme)
UKCA Aerosols (31)	+ 12% (takes a/c of saving due to CLASSIC being switched off)
UKCA Online Photolysis	+ 30%
ED-SPITFIRE-ECOSSE-FUN	+ 10%
WAVE	+ 2-8%

Table 1: Estimated cost of Earth System components relative to HadGEM3-A. The numbers in brackets for UKCA signify the number of advected tracers.

Component	Cost relative to NEMO
PlankTOM4/5/10 (22/25/39)	+ 700%/800%/1200%
MEDUSA (12)	+ 100%
ERSEM (48)	+800%
CICE and Coupling	+ 15% and +15-40%
GLIMMER	+ 2%

Table 2: Estimated cost of Earth System components relative to NEMO. The numbers in brackets for the ocean biogeochemistry models signify the number of advected tracers.

Table 3 shows the minimum and maximum cost of HadGEM3-ES at various resolutions relative to the current cost of HadGEM3-AO at N96L85-ORCA1.0L75. Table 4 shows similar costs, except that the relative contribution of the ES components is clearer. The cost of the atmosphere component of HadGEM3-AO is 40 times the cost of the ocean at N144L85-ORCA1.0L75, for example, making UKCA the most expensive of the proposed ES components at those resolutions. At N96L85-ORCA0.25L75, however, it is the OBGC (PlankTOM10) that is potentially the most expensive component. There will be a clear need to compromise between model resolution and ES component complexity.

HadGEM3-ES Resolution	Cost relative to HadGEM3-AO at N96L85-ORCA1.0L75
N96L85-ORCA1.0L75	3-5
N96L85-ORCA0.5L75	4-9
N96L85-ORCA0.25L75	8-34
N144L85-ORCA1.0L75	7-11
N144L85-ORCA0.5L75	8-14
N144L85-ORCA0.25L75	12-40
N216L85-ORCA0.25L75	30-68

Table 3: Estimated cost of HadGEM3-ES at different resolutions relative to HadGEM3-AO at N96L85-ORCA1.0L75.

HadGEM3-ES Resolution	Cost with most expensive atmosphere components and least expensive ocean components	Cost with least expensive atmosphere components and most expensive ocean components
N96L85-ORCA1.0L75	4.4	3.8
N96L85-ORCA0.5L75	5.0	7.4
N96L85-ORCA0.25L75	9.4	33
N144L85-ORCA1.0L75	9.8	7.7
N144L85-ORCA0.5L75	10	11

Table 4: Estimated cost of HadGEM3-ES at different resolutions showing the relative contribution of the atmosphere and ocean ES components.

HadGEM3-AO at N96L85-ORCA1.0L75 is currently running on the existing IBM system at 2 model years/day. HadGEM3-ES can achieve similar throughput if the cost of the model is within a factor of 2-3 (for the upgraded IBM) or within a factor of 4-9 (for the new supercomputer) of the current cost of HadGEM3-AO at N96L85-ORCA1.0L75. The estimated computational cost of HadGEM3-ES makes resolutions N144L85-ORCA0.25L75 and N216L85-ORCA0.25L75 unfeasible even with a new supercomputer and extensive optimisation. Resolutions of N96L85-ORCA0.25L75 and N144L85-ORCA0.5L75 are achievable on the new supercomputer if less expensive/complex ES components are selected (in particular, OBGC) and/or with extensive optimisation. On the other hand, if the lifetime of the IBM was extended beyond the timescale proposed for the completion of HadGEM3-ES, then the only feasible resolution would be N96L85-ORCA1.0L75 and even then, some compromise on the complexity of the ES components would be required if sufficient optimisation wasn’t achieved. Given the importance of supercomputing capability to the model resolution and ES component complexity of HadGEM3-ES, a decision in regard to MO supercomputing capability for the timescale of the HadGEM3-ES project would ideally be required before the start of the HadGEM3-ES project. However, Beddington et al. (2010) recommended that HPC requirements be reviewed in 2012.

Work to improve the efficiency of the UKCA N-R solver by the HPC team is already underway. Equally, ongoing developments aim to reduce the cost of the coupling between CICE and NEMO. It is likely that further optimisation will need to be carried out and/or limits will have to be set on the computational cost of the ES components. Either way, the HadGEM3-ES model could greatly benefit from optimisation and Paul Selwood has nominated himself to be the main point of contact for optimisation during the development of HadGEM3-ES.

14. Development Timescale

The development timescale for HadGEM3-ES is based on the anticipated lifetime of HadGEM2-ES and the scientific need for a new Earth System model. On this basis, a start date of early 2012 for the HadGEM3-ES development project is proposed, with a 4-year development timescale. The timeline for the HadGEM3-ES development can be seen in Figure 1. It indicates when certain key decisions will be made in relation to the individual Earth System components and assumes that a supercomputer upgrade will occur at the earliest date i.e. user access by September 2014. No definite decision on the IPCC AR6 timetable is expected in the near future, however, this development timescale could fit with the IPCC AR6 timescale, should it follow previous assessment reports.

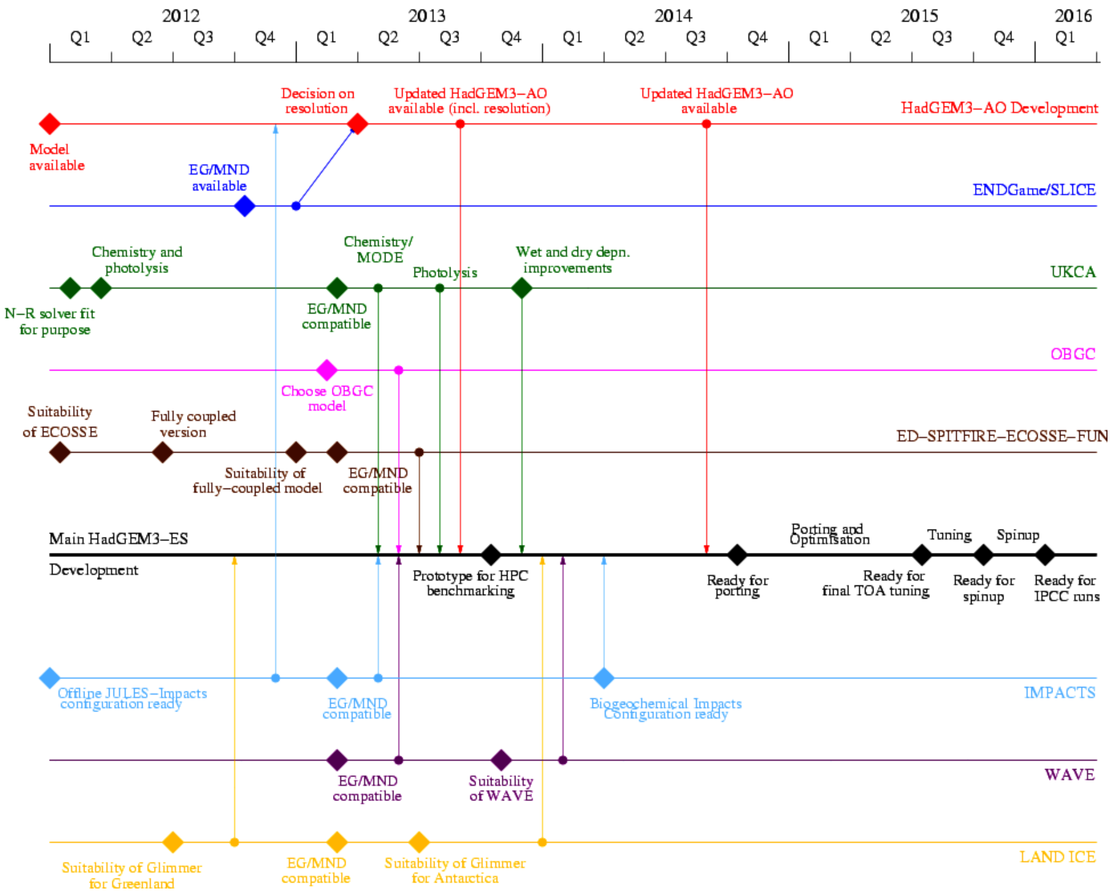

Figure 1: Timeline of the HadGEM3-ES project

15. Potential Risks and Fallback Positions

Risk no.	Description	Likelihood ([1])	Severity ([1])	Mitigation
1	Supercomputer procurement coincident with model tuning/spinup/production phase	H	H	Bring procurement forward and/or extend lifetime of IBM beyond HadGEM3-ES production runs
2	JULES-ED-SPITFIRE-ECOSSE-FUN package not ready on time	H	H	Extra resources to support JWCRP-funded PDRA at Exeter Uni. and/or prioritise ED-ECOSSE-FUN
3	OBGC sub-component not ready on time	M	H	Extra resources within CR and/or seek help from NERC partners
4	UKCA N-R solver not fit for purpose	M	H	Extra resources within CR and/or HPC team
5	UKCA chemistry scheme not ready on time	L	L	Extra resources and/or use less ambitious chemistry scheme
6	Project too ambitious	M	M	Reduce the number and/or complexity of sub-components
7	Computational cost of HadGEM3-ES too high	M	H	Reduce complexity of sub-components and/or find extra resources to optimise model
8	Not enough computing resources	M	M	Re-prioritise computing resources within CR
9	Lack or loss of key staff and expertise	M	H	Delay work in other CR areas; seek help from NERC partners

Table 4: Risks associated with HadGEM3-ES development
([1]) Key to Likelihood/Severity: H = High, M = Medium, L = Low

A list of potential risks to the success of HadGEM3-ES are listed in Table 4, along with their likelihood of occurrence, the severity of the impact if they were to occur, and actions which should be taken to minimise them. In particular, there is a far greater dependency on external developments than in previous MOHC climate model development projects. Therefore, we also discuss possible “fallback positions” for each of the most critical Earth System components.

Of the ED-SPITFIRE-ECOSSE-FUN developments, priority will be given to ED and the nitrogen cycle. However, there are doubts as to the suitability of ECOSSE. If this really is the case, then one option would be to write a soil nitrogen cycle from scratch. Although it is difficult to quantify the effort required to do this, it is hoped that an acceptable level of simplicity/sophistication could be reached fairly easily. Likewise, if for some reason SPITFIRE wasn't ready/suitable, the INPE fire model (currently being implemented in HadGEM2-ES) could be implemented along with their plume rise parameterisation. Alternatively, fire could be omitted to give priority to the other components. The ultimate "fallback" position, however, is to use TRIFFID, possibly with one additional PFT to distinguish between tropical evergreen and temperate deciduous broad-leaved trees and including carbon-nitrogen interactions.

For ocean biogeochemistry, the HadOCC model has already been coupled to NEMO for operational global ocean ecosystem forecasting and there are plans to upgrade to diat-HadOCC. This provides a suitable "fallback" position for HadGEM3-ES although it would not represent any advancement in the science over HadGEM2-ES.

In relation to UKCA, if the problems with the N-R solver are not sufficiently addressed, then the use of the Backward Euler solver from HadGEM2-ES represents a "fallback" position but would limit the choice of chemistry to tropospheric schemes. There are a number of tropospheric schemes available with greater complexity than that used in HadGEM2-ES as alternatives.

For land ice, impacts and wave modelling, although their inclusion in HadGEM3-ES is desirable, the impact of not being able to include them is less critical than for the other components. Hence, the fallback position is to prioritise which of them is included, reduce complexity, or exclude them from HadGEM3-ES.

16. Resources Required

- With the complexity of HadGEM3-ES and the high degree of external dependencies, it is particularly critical to the success of HadGEM3-ES to have a project manager and a dedicated configuration manager for the duration of the project.
- Given the ambitiousness of having a fully-coupled model with ED-SPITFIRE-ECOSSE-FUN, it is essential to have 1 person within the MOHC to work alongside the JWCRP PDRA from 2011 to ensure delivery of a model fit for purpose.
- Once the OBGC model is chosen, 1 person is required within the MOHC from early 2013 to work on this component, in particular, improving its performance, adding appropriate couplings, and assessing air-sea fluxes of CO_2 and DMS.
- The enhancements to UKCA capability proposed for HadGEM3-ES are ambitious and require 2 people from the start of the project, one focussing on the chemistry and the other on aerosols.
- Given the importance of optimisation, an appropriate level of input from the MO's HPC team will be required during the development of HadGEM3-ES.
- If a new supercomputer is procured or European supercomputing is available within the HadGEM3-ES timescale, there will be the necessity to have a co-ordinated and dedicated team to port and scientifically validate the model. For HadGEM2-ES, this team consisted of 8 scientists who liaised with members of the Climate Research Unified Model (CRUM) team.
- No extra resources are required for the wave model.
- No extra resources are required for impacts modelling.
- No extra resources are required for land ice modelling.

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