Earth System Modelling on the Earth Simulator using the NUGEM Model

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In this project we are developing an Earth System Model called NUGEM, based on the UK Hadley Centre's HadGEM1 climate model. The basic model has an atmosphere resolution of 1.875° × 1.25°L38 and ocean resolution of 1° × (0.33°–1°)L40, corresponding to the HC's IPCC AR4 configuration. The new ESM components will include carbon cycle models of the ocean (NPZD type), of the land (dynamic vegetation model, TRIFFID) and atmospheric chemistry (STOCHEM and UKCA). Multiple century integrations will be performed, to enable us to directly assess the impacts of climate and its variability in fundamentally important areas such as agriculture, water resources, energy, air quality and human health. With the aim of starting to resolve the extremes of weather and climate, such as heat waves, floods and typhoons higher resolution versions of HadGEM1 (atmosphere 1.25° × 0.83°L60, ocean 1/3° × 1/3°L40) will also be developed. These higher resolution models will also be extended into Earth System Models.

Keywords: Earth System Model, carbon cycle, climate, chemistry

1. Introduction

The Earth Simulator Center (ESC), the Centre for Global Atmospheric Modelling (NCAS CGAM) University of Reading and the Met Office's Hadley Centre (HC) signed a Memorandum of Understanding (MOU) for 5 years in 2002, to collaborate on advanced climate system research. The Implementation Agreement for the MOU sets out the details of a 3 year collaborative project starting in January 2005 involving six UK scientists, of whom four are based at the ESC. This project has as its goal the development of models of the Earth System, to include climate, carbon cycle, chemistry and ecosystem processes at both medium and high resolution. Such models will allow us to begin to explore how climate interacts with the natural environment and how such feedbacks might change in future climate regimes.

The Earth Simulator supercomputer allows us to realistically advance the deployment of this next generation in climate modelling. The expertise of the groups at the ESC both in fully exploiting the power of the machine and in the development of advanced numerics for high-resolution dynamical cores will enable the project to extend the scientific reach and understanding of such complex systems.

2. Project status

After some visits to Yokohama by British scientists in past years to establish the UK-Japan Climate Collaboration (UJCC), an implementation agreement with the ESC research group was drafted in late 2004 by NCAS and the HC project managers, so that discussions and planning of the practical aspects of the joint work have been initiated and are on-going. The UJCC project was officially launched on 19 January at the UK Embassy in Tokyo, with an introductory speech by the Foreign Secretary, Jack Straw and then scientific talks by Prof. T. Sato (Earth SImulator Center Director), Dr. D. Griggs (Hadley Centre Director), Prof. J. Slingo (NCAS CGAM Director) and Dr. N. Nikiforakis, Univ. of Cambridge. A wide attendance by Japanese scientists, major scientific and government agencies, and the

media, assured a global coverage, including TV, radio and printed interviews on the BBC, The Independent, and Russia's Channel 1. More detailed information, including examples of the media coverage, can be found here: http://ncas.nerc.ac.uk/news/stories/uk_japan_collab_launch05.asp.

The UJCC home page was also updated to contain the latest project details (http://www.earthsimulator.org.uk), but mainly a project brochure was designed and produced, in collaboration with Hadley Centre, to be distributed "in hand" and via the WWW. This can be found here, in PDF format: http://www.earthsimulator.org.uk/launch.php.

In the weeks following the launch, the four resident scientists (2 NCAS, 2 HC) were busy searching for homes, but at the same time the team of six managed final installations of the UK Meteorological Office's Portable Unified Model (UM), PUM-5.5 and the corresponding UM User Interface (UMUI). This allowed for the reproduction of several simulations already executed on UK supercomputers, and permitted the first significant performance tests, with the compilation of the first statistics based on different combinations of number of processors and model configurations. In April 2005, installation of a PUM-6.0-based HadGEM1 (the Hadley Centre's new climate model used for its IPCC AR4 contributions), reflecting the model code and structure as optimized on the Met Office NEC SX6 machine, has been completed and a final installation of a UM-6.1 library (latest version available at the HC) has been initiated. The same code will be used by the Hadley Centre, CGAM and UK-HiGEM projects (the latter developing the high resolution version of HadGEM1) which will make collaboration much easier, and allow model developments and new science to be incorporated without extra effort.

One of the most important initial tests of the model on the ES system is to check that the science produced by the model here is equivalent to that produced in the UK (to ensure that compilation and model integration are working correctly). To that end a thorough validation and verification process is now ongoing, using techniques developed at the Hadley Centre in their T3E to NEC supercomputer model porting. This involves running control, perturbed and ported versions of the code and checking that the variability in ported model solutions is within the envelope of internal variability that can be excited in the control simulation, by perturbing initial conditions. Once this process is complete we can begin innovative with multi-year science validations (against well-established climatological data sets) and the set of new integrations.

Monitoring and profiling of the model simulations on the ES system have shown performance which is similar to UK NEC systems at the UKMO. Currently work is ongoing investigating scaling performance of the code on multiple ES nodes. So far this work has identified a few sections of the code which are not scaling as well as might be expected. These include IO performance, collective operations, and load balance issues. Modifications are ongoing and some early improvements can be seen from test HiGEM ocean experiments shown in Figure 1.

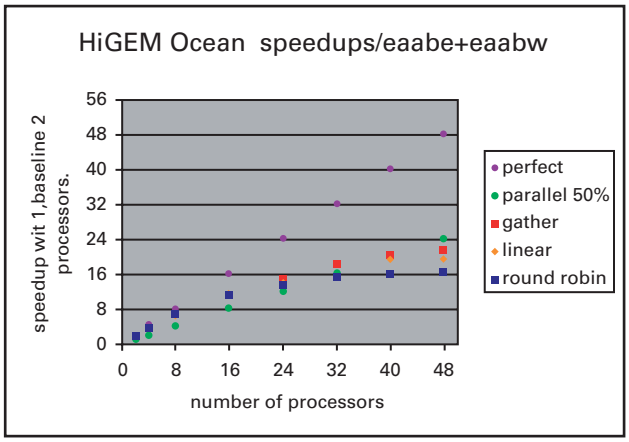

Fig. 1 Performance of an early version of the HiGEM ocean model code, showing reasonable scaling to 16 processors. Performance is influenced by how the model is decomposed, with a linear decomposition (that is, spatially adjacent parts of the model are run on adjacent processors) being an improvement over round-robin decomposition.

Given the need for extremely high storage requirements (order of hundreds of TB), a very important recent achievement of the collaboration was the establishment of a direct connection between the ESC data archive and the British Atmospheric Data Centre (BADC), which will hold and distribute all projects results to the UK and international scientific collaborators. The link has been successfully tested and operated in the last months, although performance issues will need further work before the link can be used effectively.

3. Aims and objectives

The principal aim of the project, using the unprecedented computational resources available at ESC, is to combine resolution and complexity in addressing current scientific themes in climate system research. As a start, building upon the standard HC IPCC AR4 model (HadGEM1), a spin-up and control run of the fully coupled NUGEM (Nihon-UK Global Environment Model) will be performed in the coming year. This model will be an improved version of HadGEM1 model and additionally will include the fully interactive carbon cycle for the ocean and atmosphere/land surface. Together with a range of reference integrations to calibrate the impact of different parameters, initial and boundary conditions (such as land surface usage changes), we will:

- Investigate feedback loops involving:
  - Warming and enhanced CO_2 release from soil carbon

- ◦ Vegetation feedbacks e.g. Amazon die-back
- ◦ Overlooked thresholds in the climate system, e.g. assumptions about physiological mechanisms in current ecosystem models
- • Test whether these feedbacks differ from previous models and how they may impact our estimates of climate change

In particular we will examine whether the enhancement by 50% in the atmospheric CO_2 due to inclusion of the carbon cycle in the Cox et al. (2000) paper is reproducible, or whether results give the much more modest feedbacks seen in other models (e.g. Kawamiya et al., 2005; Friedlingstein et al., 2001).

We will also begin a control integration of the HiGEM model and examine the impact of resolution on the coupled climate model by comparing with HadGEM1 and other models. Since HadGEM1 and HiGEM models have very similar physics and dynamics, this should make it easier to disentangle the resolution issue from other model differences. We hope to be able to work with Japanese scientists and investigate whether similar resolution dependencies are found between all our models. From the work of Guilyardi et al. (2004) there are indications that the atmosphere resolution controls some of the most important causes of climate variability, such as ENSO. Roberts et al. (2004) demonstrated that improved ocean resolution greatly improves the fidelity of the ocean simulation, but that much of this detail is lost to the coupled system if the atmosphere resolution is inadequate to resolve the small-scale ocean features. The groups working at the ESC are in a very strong position to investigate such resolution issues and discover if resolution is crucial for realistic large-scale climate simulation.

As a later development, in collaboration with Japanese scientists, we will implement the STOCHEM Lagrangian chemistry model into the NUGEM model and begin time-slice experiments. Work at the Hadley Centre and elsewhere suggests that future predictions of tropospheric ozone concentrations, and other gases, are not useful unless account is taken of changes to the climate, since chemistry is sensitive to atmospheric temperature and moisture.

4. Model configurations

An initial target resolution of 1.875° × 1.25° (N96L30) was identified, together with the first scientific target, which is the simulation of a fully integrated carbon cycle, never attempted so far. A final target resolution was envisioned at 0.833° × 0.5° (N216L60), on a centennial time scale, pending more refined performance estimates on the ES. Agreements with the many research groups involved were also reached on model development schedules, with two individual model cycles of 18 months each between production phases. A strong level of coordination with the HiGEM project was also necessary, in order to guarantee a free flow of model developments and open collaborations between HC, ESC-UJCC, HiGEM and the UK academia. As an immediate result, the HiGEM project is also migrating to the PUM6.0-based HadGEM1 as their standard development library.

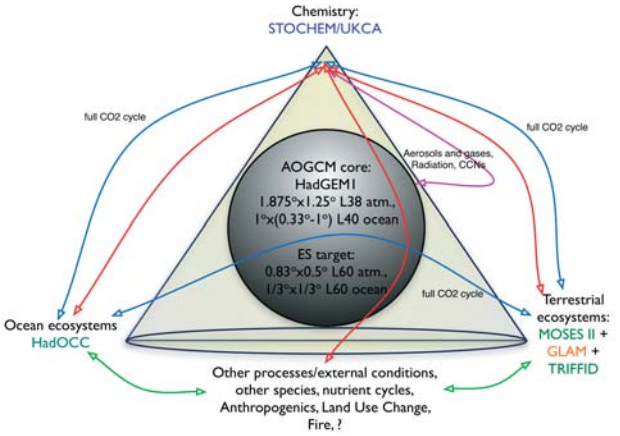

Fig. 2 The main model components available for the HadGEM1 family of models. GLAM is the General Large-area Crop Model being developed at the University of Reading.

A range of model configurations are available from UK groups which can begin to be optimized for the ES; the components are shown in Figure 2 and explained below.

1. HadGEM1 – the Hadley Centre IPCC AR4 climate model: 1.875° × 1.25°L38 atmosphere (N96/L38), 1° × (0.33°–1°) L40 ocean, EVP/ITD sea-ice, MOSES2 land surface scheme, interactive aerosols – see Johns et al. (2004)
2. HadGEM1+carbon cycle models HadOCC (ocean NPZD scheme – see Palmer and Totterdell, 2001) and TRIFFID (dynamic vegetation land surface scheme, see Cox, 2001)
3. HiGEM – 1.25° × 0.83°L38 atmosphere (N144L38), 1/3° × 1/3°L40 ocean – high resolution version of HadGEM1 model with some improved schemes. Increase to 0.833° × 0.5°L60 (N216/L60) atmosphere resolution by end of project.
4. HadGEM1 + tropospheric chemistry model STOCHEM (see Collins et al., 1997)

Acknowledgements

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NUGEM による地球シミュレータ上での地球システムモデリング

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キーワード: Earth System Model, carbon cycle, climate, chemistry

地球シミュレータセンター(ESC)、グローバル大気モデリングセンター(NCAS CGAM レディング大学)とMetOffice ハドレーセンターは、2002年に先進的気候システム研究開発における5年間の共同研究の覚書(MOU)にサインし、それが本プロジェクトの出発点である。本プロジェクトは2005年1月19日に東京の英国大使館(東京)において、外務大臣Jack Strawの基調演説、佐藤哲也博士(地球シミュレータセンター長)のスピーチとともに、D. Griggs博士(ハドレーセンターディレクター)、J. Slingo教授(NCAS CGAMディレクター)とN. Nikiforakis博士(ケンブリッジ大学)らにより公式発表された。この報道に関する詳細な情報は以下に報告されている。http://ncas.nerc.ac.uk/news/stories/uk_japan_collab_launch05.asp.

このプロジェクトでは、イギリスハドレーセンターのHadGEM1気候モデルに基づいて、NUGEM (Nihon-UK Global Environment Model)と呼ばれるEarth System Model (ESM)を開発している。ハドレーセンターにおいて第4次IPCCレポートAR4の報告に寄与するモデルに匹敵する、1.875° × 1.25°鉛直38層 の大気と、水平解像度1° × (0.33°から1°)鉛直40層の海洋モデルの結合モデルであり、さらに、海洋における炭素循環モデルや(NPZDタイプ)、陸面モデル(動的植生モデル:TRIFFID)と大気化学モデル(STOCHEMとUKCA)を含んでいる。このモデルを用いて複数世紀にわたる予測計算を実行する予定であり、その結果、農業、水資源、エネルギー、大気汚染や人間の健康などに対する気候やその変動のインパクトを直接的に評価することが可能となる。また、熱波、洪水や台風などの、気象や気候における激しい現象を解析する目的で、より高い解像度のHadGEM1 (大気解像度:水平1.25° × 0.83° 鉛直60層、海洋解像度:水平1/3° × 1/3° 鉛直40層)を開発する予定である。これらのより高い解像度のモデルの知見もまた、ESMに反映する予定である。

2004年度は、Met Officeで使用されているPortable Unified Model (UM) PUM-5.5、およびUM User Interface (UMUI)の最終的なインストールを行った。 これにより、既に英国で実行されたシミュレーション結果を地球シミュレータ上で再現し、モデル開発の初期段階で必須となる重要なシミュレーション性能テスト、つまり地球シミュレータ上とMet Officeにおいて得られた結果が同値であることの検証が可能となった。ハドレーセンターにおいてT3EからNECスーパーコンピュータに移植した際に培われた知見を駆使して、現在徹底的な検証が進行中である。さらに、地球シミュレータ上での計算性能最適化のための作業も同時平行的に行っており、地球シミュレータセンターとも協力をしながら進推している。(図1)

共同研究における非常に重要な最近の懸案として、シミュレーション結果を保持するための大規模なデータストレージ(数百TBのオーダー)が必要であることから、地球シミュレータに付属するデータアーカイブと英国のAtmospheric Data Centre (BADC)との間のネットワーク通信性能分析とその向上のための工夫を検討している。 BADCはシミュレーションによって得られたすべての結果を保存し、近い将来、英国の科学者および共同研究者に公開する予定である。このことは、地球シミュレータによる成果を世界の科学者の共通の財産として位置づけることを可能とすることであり、現在、データの効果的な使用法についての検討とテストが継続されている。

2005年度は、さらにプロダクト計算実験も開始される予定であり、より加速的なプロジェクトの展開を予定している。

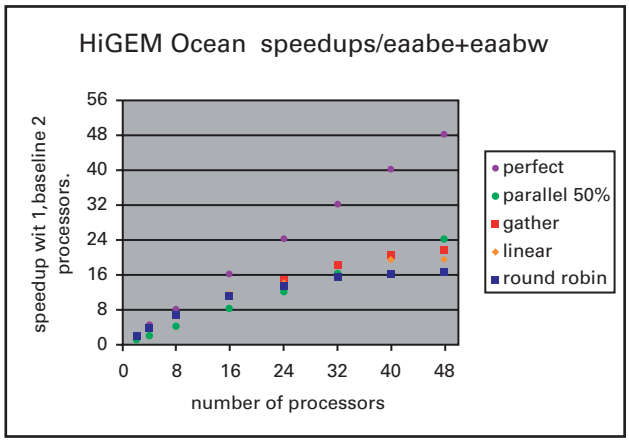

図1 HiGEM海洋モデルコードの初期バージョンの計算性能。16プロセッサにおける妥当なスケーリングを示している。性能は、線形分割(すなわち、空間的に隣接している部分は隣接したプロセッサ上で実行)による分割法により影響を受ける。

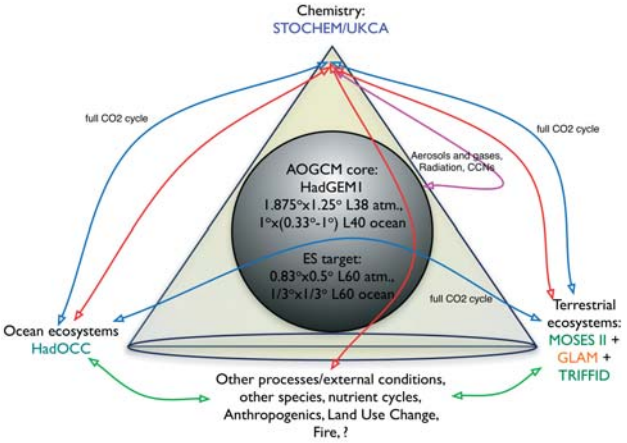

図2 HadGEM1に関する関係機関で利用可能な主要コンポーネント。GLAMはReading大学で開発されたGeneral Large-area Crop Modelをさす。