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 atmospheric resolution of 1.875° × 1.25°L38 and oceanic resolution of 1° × (0.33°–1°) L40, corresponding to the HC's IPCC AR4 configuration. With the aim of starting to resolve the extremes of weather and climate, such as heat waves, floods and typhoons, the advanced resolution model (NUGEM) adopts an atmospheric resolution of 0.83° × 0.56°L38 and will use on oceanic resolution of 0.33° × 0.33°L40. Using a model chain which includes systematic, incremental resolution steps, multiple decadal to century-long 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. These higher resolution models will also be extended in the future for applications in Earth System Modelling.

Keywords: Earth System Model, resolution, 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 aim of this collaboration is to exploit the power of the Earth Simulator (one of the world's most powerful supercomputer, located in Yokohama, Japan) to produce ground-breaking climate simulations which could not be achieved elsewhere. A key scientific goal is to develop a range of models, based on the Hadley Centre's HadGEM1 [1] family, including 150 km, 100 km and 60 km atmosphere and 100 km and 30 km ocean models [7], which will enable the representation of smaller scale processes at higher resolution. Analysis of such models will concentrate on understanding how the large-scale mean climate is changed by such emergent processes, and hence will help to reduce model uncertainty and build capability. Results from this work will feed directly into the development of the next Hadley Centre coupled model HadGEM2.

2. Project status

During the course of 2005, final installation of the UK Met Office UM-6.1 library (latest version available at the HC) has been completed, together with standard validation of base experiments, over several decades. The same code is currently used by the Hadley Centre, CGAM and UK-HiGEM projects (the latter developing HiGEM, the mid-resolution version of HadGEM1) which will make collaboration much easier, and allow model developments and new science to be incorporated without extra effort. Several bug fixes, improvements to physical packages and optimisations have been incorporated through this multi-institution collaboration.

Model development

Development of models based on HadGEM1a science but with enhanced resolution has continued through the year. The HiGEM model (100 km atmosphere, 30 km ocean) was improved and made computationally stable both by changing the sea-ice time-stepping algorithm (done in conjunction with the NERC-funded UK-HiGEM project) and by fixing errors in the creation of model orography fields.

The NUGAM model (60 km atmosphere) has been derived using expertise from the operation of the Met Office's global forecast model (pre-November) and the full set of climate packages in HadGEM1. Problems with model orography, numerical instability in the Himalayas, ozone forcing, noise and grid-point storms have been addressed with much help from Met Office staff, and this model shows promising early results. Some of these developments have flowed back to UKMO and helped research on improving the current numerical weather prediction model.

To examine the relative importance of resolution in the components of a coupled model, a cross-resolution model incorporating the HiGEM atmosphere and the HadGEM1 ocean has also been developed.

Model optimization

Significant progress has been made during the year regarding the performance of the models on the Earth Simulator. Using the HiGEM model (100 km atmospehere/ 30 km ocean coupled model), a thorough analysis of model performance was undertaken. This demonstrated that, in particular, the Input/Output functions of the model performed poorly when attempting to use many computational nodes. Code was written to improve this performance by dedicating processors to the I/O functions, and this benefits the model when run on many nodes.

Part of the reason for the development of the NUGAM model was to make it possible to address atmospheric scales (including weather) that we believe to be important for the simulation of fundamental elements of the climate system. After identifying and removing important model bottlenecks, especially in the treatment of IO and communications, NUGAM has shown the ability to make meaningful use 11 or more nodes of the Earth Simulator (see Figure 1).

Overall 2005 performance gains from optimisation work on the Earth Simulator, across our entire suite of models, have ranged from 30% to 200%.

Science

The main analysis during the year has focused on the HiGEM integration, and in particular the tropical Pacific performance of this model. The HadGEM1 model has a large-scale cold bias in that part of the world, which is a coupled error caused by too-strong winds and too-cold sea surface temperatures, which are crucial when trying to simulate El Niño [6]. The HiGEM integration has a realistic simulation, and the main cause of this improvement is being investigated. One likely explanation involves the role of tropical instability waves in the ocean, which cause changes in sea surface temperature of several Kelvin, and interact with the atmosphere by changing the structure of the boundary layer. To understand the mechanism further, sea surface tempera-

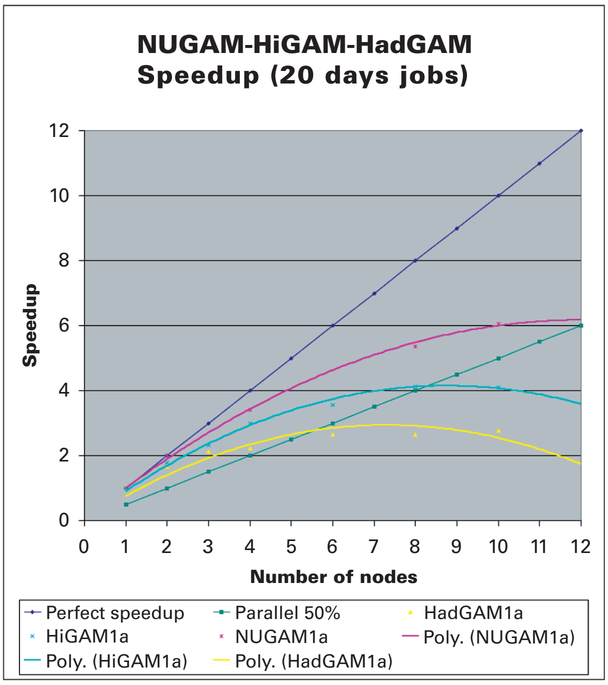

Fig. 1 The speedup factor of individual members of the UJCC model chain on the Earth Simulator: HadGAM (N96), HiGAM (N144) and NUGAM (N216), as dependent on the number of nodes used in the integration.

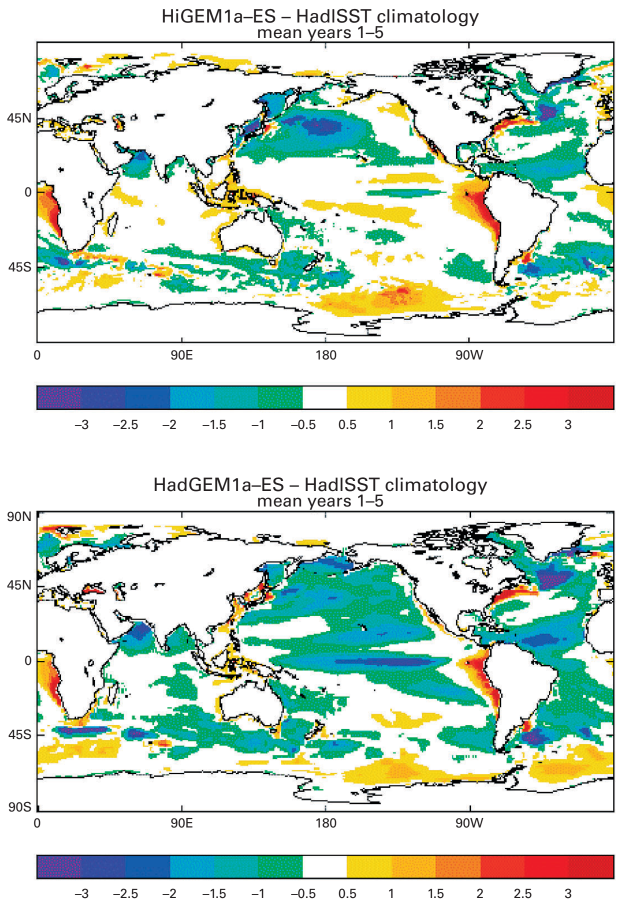

Fig. 2 Sea surface temperature errors for (top) HiGEM1 and (bottom) HadGEM1 compared to HadISST climatology, averaged over the first 5 years of integration.

tures diagnosed from the coupled model, and then altered by selective filtering, are being used to force the atmosphere-only model, to see if the changes can be identified in the mean atmospheric circulation.

Another area of interest is the sea-ice simulation, which also changes with model resolution. The HiGEM simulation generally has less sea-ice in summer in the Arctic than both the low resolution model and climatology, but simulates the winter rather well. It is thought that differences in the winds at high resolution cause part of this change. In the Southern Hemisphere there is a markedly different behaviour between groups of models at both high and low resolution - one common factor is the ocean equation of state, and this will be investigated further.

There have been some early integrations of the NUGAM (60 Km atmosphere) model, and these are already demonstrating improvements in local climate. The enhanced resolution of orography means that precipitation patterns are improved, which may have significant consequences for the water budget and vegetation dynamics [3]. As an example, Figure 3 shows the precipitation patterns over Europe from model climatologies at 150 km, 100 km and 60 km resolution, and from CRU data. For Europe, where significant precipitation in the Spring is controlled by the interaction of large scale storms with topography, some important regional information stands out: the N-S distribution in Iceland, the E-W distribution in the British Isles, the N-S distribution for the Alps and coastal points for the Scandinavian Alps. It is very interesting to notice that the N96 model is unable to distribute precipitation correctly over Western Europe, missing completely the maxima over the Alps and raining instead over much of France. Somewhat surprisingly, only the N216 model is capable of reproducing the large scale E-W European distribution of precipitation and to also concentrate precipitation on narrow gradients all throughout the coasts of the Mediterranean, including the Eastern boundary of the Adriatic Sea.

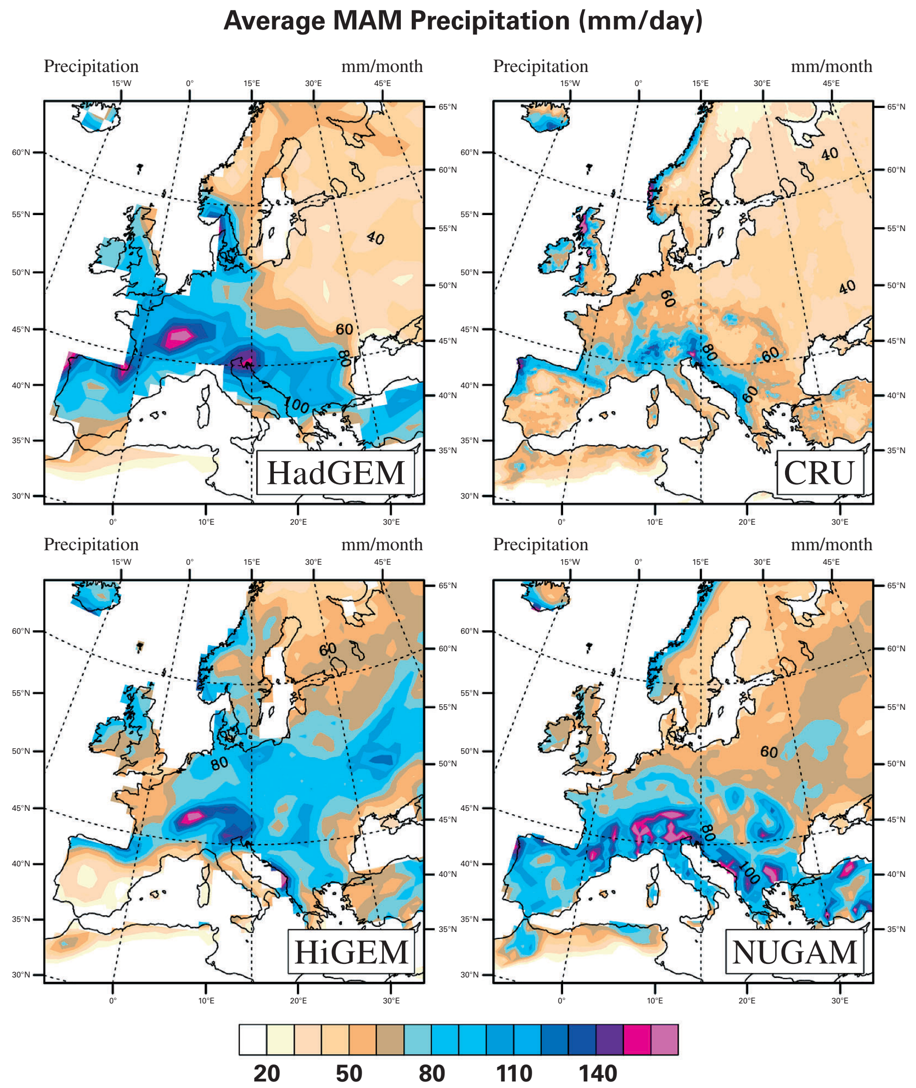

Fig. 3 UJCC model chain simulations of MAM precipitation for Western Europe: CRU observations (top right), HadGEM (N96, top left), HiGEM (N144, bottom left), NUGAM (N216, bottom right).

3. Aims and objectives for 2006

In accordance with the principal aim of the project we will continue 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 completed in the coming year. With its high resolution, such a model can begin to properly resolve weather features and allow more in-depth analysis of regional climate processes. Being a global model, it will also allow investigation of important climate sensitivity issues such as cloud and albedo feedbacks, land-atmosphere coupling, ocean heat uptake. We intend to continue to use the expertise and knowledge gained in building this advanced model to improve the lower-resolution models.

We will also continue with the control integration of the HiGEM model and examine the impact of resolution on the coupled climate model by comparing with HadGEM1 and other models at ESC. These integrations will also complete the model resolution chain from 150 km to 60 km models, giving an unprecedented resource for understanding the role of resolution. Since all members in our modelling suite 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.

Acknowledgements

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キーワード：Earth System Model，resolution，climate，chemistry

本プロジェクトでは、英国ハドレーセンターのHadGEM1気候モデルに基づき、NUGEM（Nihon-UK Global Environment Model）と呼ぶ地球システムモデルを開発している。基本とするモデルHadGEM1は、大気大循環モデルが水平緯度1.875°、経度1.25°L鉛直38層、海洋大循環モデルとしては水平解像度が経度方向に1°、緯度方向に0.33°から1°、鉛直40層の、気候変動に関する政府間パネル（The Intergovernmental Panel on Climate Change: IPCC）第4次評価報告書（AR4）のために設定したモデルである。本プロジェクトで新規開発しているモデルNUGEMでは、熱波、洪水、台風などのような気象、気候現象における顕著現象をターゲットとしているので、大気大循環モデルは緯度0.83°、経度方向0.56°、鉛直38層、海洋大循環モデルとしては水平0.33°鉛直40層の解像度を採用する予定である。数10年スケールから100年スケールの積分を実行する予定であり、この実験により、農業、水資源、エネルギー、大気環境、健康などの重要な基盤分野における、気候やその変動のインパクトを直接評価することが可能となる。

2005年度は、The UK Met Office UM-6.1ライブラリの最終実装を完了し、加えて、数10年規模の、基礎的検証のための数値実験を終了した。これらに使用されているコードは、ハドレーセンター、CGAM、UK-HiGEMプロジェクト間で共通のコードであり、それらのプロジェクト間における、モデル開発や研究に関する様々な情報交換を容易にしている。

モデル開発：

HadGEM1aを基盤にした高解像度シミュレーションにむけた開発を継続し、HiGEM モデル（大気大循環モデル：水平解像度100km、海洋大循環モデル：水平解像度30km）は、安定に実行可能となった。NUGAM モデル（大気大循環モデル：水平解像度60km）についても、地形に起因する不安定計算の解消など、多くの課題をUK Met Officeからのサポートで解決し、さらにその結果を彼らにフィードバックし、現時点における現業予報モデルの精度向上へも貢献している。加えて結合モデルの解像度を向上するために、高解像度シミュレーションを前提とした大気HiGEMと海洋HadGEM1のモデルについての開発も進めている。

モデルの計算性能最適化：

計算性能の最適化においては、大きな進展があった。HadGEMモデルでは、モデルの詳細な計算性能評価を行い、入出力の扱いにおいて課題があることが明らかになった。NUGAM モデルの開発では、上記の点を考慮し、入出力とコミュニケーションにおけるボトルネックを解消した結果、地球シミュレータ上において11ノード以上での実行が可能となった（図1）。

サイエンス：

HadGEM1では、太平洋熱帯域において、大規模なスケールの低温バイアスがあったが、HiGEMでは、そのバイアスが改善された。現在、改善されたメカニズムを解析中であるが、海洋の熱帯不安定波がKelvin波により海洋表面の温度を変化させ、さらに大気境界層の構造を変化させたことによる大気海洋相互作用に起因する、ということができる。さらに詳しい解析を、結合モデルによって得られた海洋表面温度を大気モデルコンポーネントの強制力に用い、その変化を解析することにより進めている。

海氷のシミュレーション結果についても、解像度によるインパクトが明らになってきており、HiGEMでは、より低解像度の気候モデルと比較すると、夏季の北極海での海氷が少なく、むしろ冬季の方がよく再現されている。これは、高解像度による風の分布が異なることに起因すると考えられる。南半球

では、さらに解像度の違いによる大きな差があることがわかっているが、これらについては現在も解析中である。

NUGAMモデル（大気の水平解像度：60Km）では、局所的気候における、特に、解像度を高くしたことによる地形性降雨分布の改善が得られた。図2は、150km、100km、60kmの水平解像度におけるヨーロッ域の降雨パターンである。HadGEMモデル（水平解像度135km）では、アルプス領域の降雨を再現できず、フランスに多くの降雨をもたらしているが、NUGAMN216（水平解像度60km）モデルは、大規模スケールの降雨分布と地中海岸域の非常に狭い集中的な降雨を再現できた。

今後の予定：

NUGAM のコントロールランを継続するとともに、高解像度の気象特性を解像できるモデルを用いて、領域気候過程についてのさらなる解析を進める。さらに、HiGEMモデルの高解像度化によるインパクトについても、HadGEM1やESCで開発されたモデルと比較検討する。さらにダイナミカルコアや物理過程など、モデルの構成要素がほぼ同じである、しかし異なるモデルにおいて、解像度に起因する共通の課題を克服することを目指して、日本の研究者との研究交流を推進する予定である。

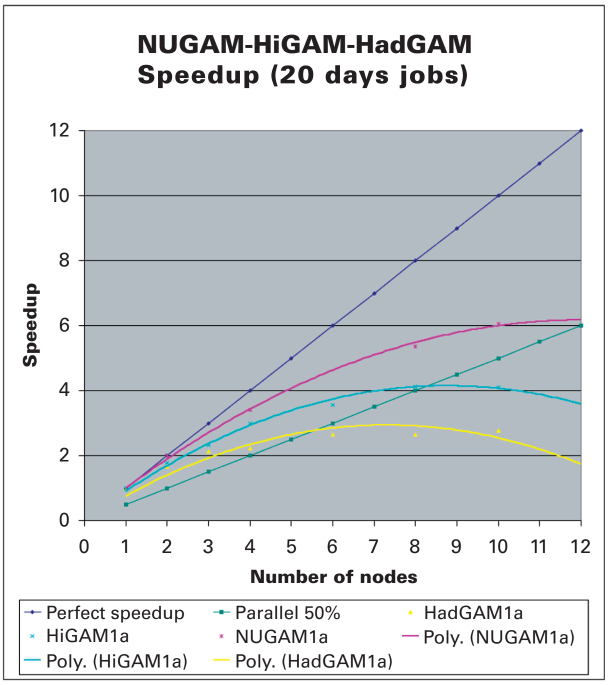

図1 地球シミュレータ上での計算性能：HadGAM（N96）、HiGAM（N144）and NUGAM（N216）、それぞれに対する結果。

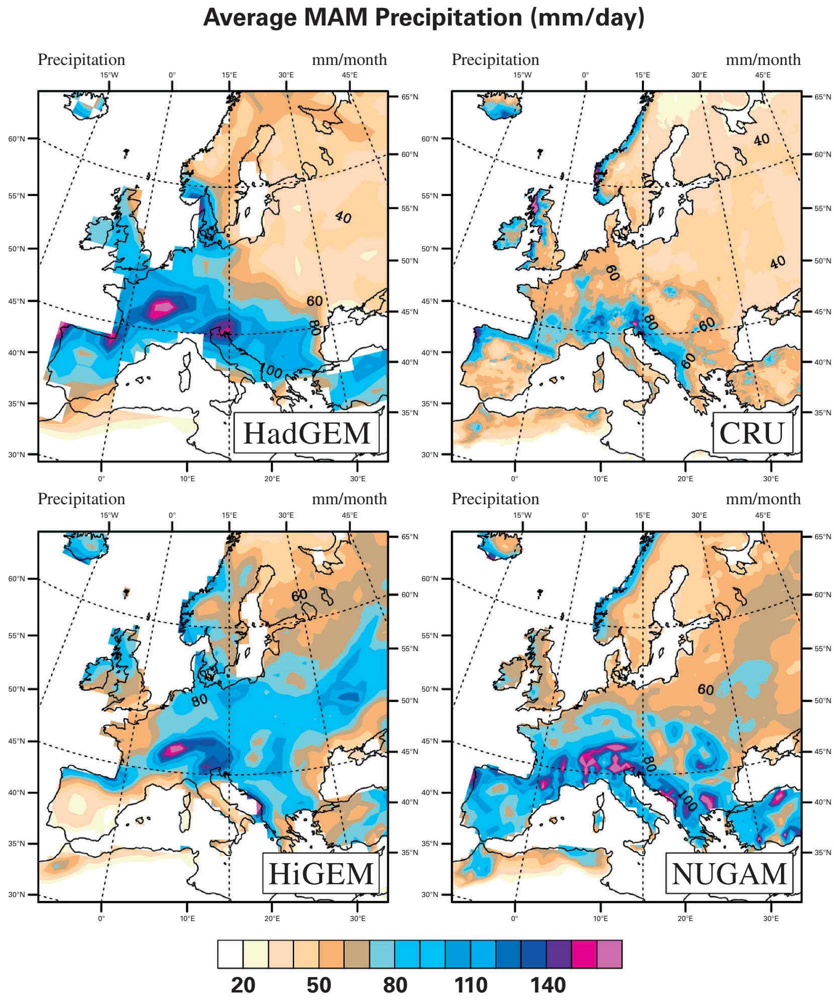

図2 西ヨーロッパにおける3、4、5月の降雨分布: CRU観測データ（上右）、HadGEM（N96, 上左）、HiGEM（N144, 下左）、NUGAM（N216, 下右）。