

# Large Atmospheric Computation on the Earth Simulator : Production phase of the LACES project

## Project Leaders

**Gilbert Brunet**      Recherche en Prévision Numérique, Meteorological Service of Canada  
**Michel Desgagné**    Recherche en Prévision Numérique, Meteorological Service of Canada  
**Wataru Ohfuchi**     The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

## Authors

**Michel Desgagné** <sup>\*1</sup>, **Wataru Ohfuchi** <sup>\*2</sup>, **Gilbert Brunet** <sup>\*1</sup>, **Peter Yau** <sup>\*3</sup>,  
**Yuki Furukawa** <sup>\*4</sup>, **Ron McTaggart-Cowan** <sup>\*5</sup> and **Michel Valin** <sup>\*1</sup>

\* 1 Recherche en Prévision Numérique, Meteorological Service of Canada

\* 2 The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

\* 3 Department of Atmospheric and Oceanic Sciences, McGill University

\* 4 Ocean Research Institute, The University of Tokyo

\* 5 State University of New York at Albany

The Canadian MC2 community model was fine tuned and tested on large number of ES' processors to demonstrate performance and scalability.

The dynamics kernel alone can actually sustained 3.1 Gflops per processor for an aggregate performance of 12.3 Tflops on 3960 processors. The production runs started in September 2004 and are now completed. A 4.5 Tbytes database is being assembled at Recherche en Prévision Numérique in Montreal. A coarse inspection of the model output reveals that the spinning, tracking and final depth of the tropical phase of hurricane Earl are all very well simulated.

**Keywords:** The Earth Simulator, hurricane Earl, ultra-high resolution simulations, life cycle of hurricane, extratropical transition and redevelopment of hurricanes

## 1. Introduction

After demonstrating basic performances and scalability of the MC2 model on a large number of ES' processors, production started in September 2004. The full life cycle of hurricane Earl (September 1998) has now been simulated at 1 km over a very large domain. A database is being built at Recherche en Prévision Numérique in Montreal-Canada. Diagnostic studies have started.

## 2. Scalability and performance

Before starting the production run with the MC2 model, a few tests were to be done in order to ensure efficiency and scalability of the code. Given a long history with vector processors at the Canadian Meteorological Center (CMC), it is of no surprise that the code already vectorizes to more than 98%. The OpenMP parallelism not being completed yet, only the scalability of the Distributed Memory (DM) code on a large number of processors was demonstrated [1]. This was done using first a scalable problem size. In order to take advantage of the full vector length and considering that

most of the MC2 code is vectorized along NI, it is best to design sub domains that have local NI as close as possible to a multiple of 256 which is the current vector length on the ES' processors. This will of course limit the size of the other horizontal dimension NJ if one is to make the sub domain as small as possible. We found that a sub domain shape of 500x50 achieves a good compromise between computational load, communication and memory size to fit on a single processor. This shape offers almost 2 full vector lengths and yet is not really demanding in terms of inter-processor communications despite the narrow rectangular shape.

One can now establish a time to solution running the model on a single sub domain for a certain number of timesteps. We then construct various global domain sizes by assembling together those unit 500x50 sub domains. Running the model for the same number of timesteps using the same number of processors as there are sub domains should in principle yield the same time to solution. This of course is not entirely true for a global domain composed of 1 to about 9 sub domains as communication patterns set in and

somewhat break a bit of the scalability. From then on however we were able to demonstrate almost perfect scalability for up to 1120 processors. This exercise also helped put to rest one major concern we had about the convergence of the iterative solver as the global problem size becomes larger and larger. It turns out that the number of outer iterations performed by GMRES [2] barely increases by 1 to 3 as the global problem size increases from 500x50 to 5000x5600. From this point we were already confident that the code would scale to 3960 processors on the targeted global domain of 11000x8640.

Scalability tests were also performed on fixed size problems in order to satisfy requirements of the ESC regarding the attribution of resources. To that effect the maximum number of processors 'M' the ESC will allow an application to run on is based on the parallelization ratio  $\alpha$  and is given by:

$$M \leq \frac{2 - \alpha}{1 - \alpha} \quad (1)$$

with

$$\alpha = \frac{T_n - T_m}{\frac{m-1}{m} T_n - \frac{m-1}{m} T_m} \quad (2)$$

where:

- $T_n$  = execution time on n processors
- $T_m$  = execution time on m processors
- ( $m > n$ )

We achieved early on enough scalability to be allowed 140 nodes. With these resources we were able to fit a global problem size of 5000x5040x51 with subdomains of size 500x45x51 when running on the full 140 nodes using a 10x112 processor topology. This produced a wall clock time to solution of 2366 sec. In order to minimally affect the vector length, the same run was then performed using a 10x56 processor topology. This yielded a wall clock time to solution of 4553 sec. Using these results to compute the parallelization ratio  $\alpha$  will give a value of 99.9927% which leads

to  $M < 13686$ . Of course this is well above the ES total computing resources and only means that the code scales very well. From this point the project was allowed the required 495 nodes and production could indeed start. Preliminary tests on the full scale 1 km domain with dimension 11000x8640x51 using a 22x180 processor topology were performed in May 2004. The MC2 model version 4.9.7 globally sustained 2.5 GFlops per processor for an aggregate speed of 9.9 TFlops. The dynamic kernel alone sustained 3.1 GFlops per processor for an aggregate performance of 12.3 TFlops. The total memory required to fit such a large problem is 7.5 TBytes.

### 3. Configurations

The goal of this first LACES project is to produce a 1 km horizontal resolution simulation over a very large domain (see ESC annual report 2003-2004) which covers the tropical phase and extra tropical redevelopment of hurricane Earl (1998). The grid strategy is a triple self-nested grid system that starts with a 50 km resolution outer domain driven by CMC analysis which is used to drive a 10 km resolution domain which in turn is used to drive the targeted 1 km resolution domain. The timestep are respectively 240, 60 and 6 seconds for the 50, 10 and 1 km domains. A Kain-Fritsch cumulus parameterization scheme is used for the 50 and 10 km domain. The precipitation is entirely explicit at 1 km using a complex micro-physics package. All runs are performed with an explicit horizontal diffusion scheme using a  $\nabla^6$  function that removes 10% of the  $2 \Delta x$  signal every timestep. It turns out that with a 6 seconds timestep we get a ratio a bit larger than 1.0 between wall clock computing time and simulation time i.e. it takes a bit more than 1 hour of wall clock computing time to simulate 1 hour. We therefore expect to use over 8 days of computation on 495 nodes to complete the task.

Because of predictability concerns over such a long integration period, we decided to reconnect the model to the

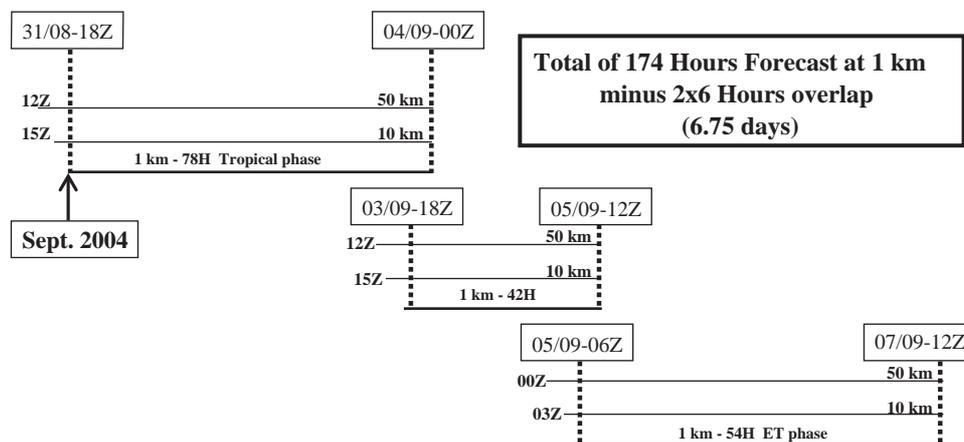


Fig. 1 Time strategy for the Simulation of the Full Lifecycle of Hurricane EARL on the ES

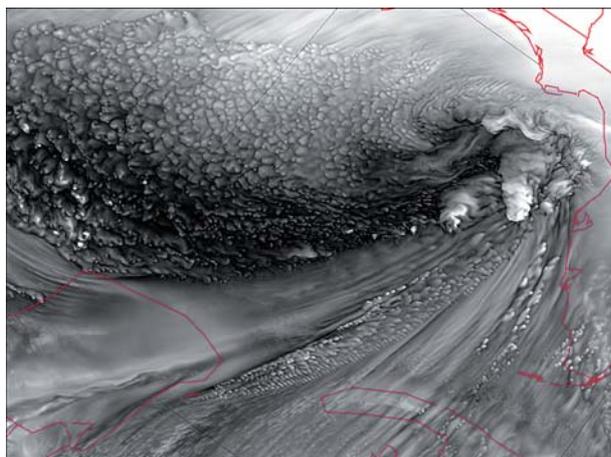


Fig. 2 45-Hour forecast of near surface specific humidity valid 15:00 UTC September 2 1998. Hurricane Earl is at this stage fully developed and is about to landfall on western Florida State

analysis at the end of the tropical phase and at the end of the transition phase (fig. 1). A 6 hour time overlap is used to spin up the model and the physics.

#### 4. Current status

The production runs started in September 2004. Since we are currently using over 75% of the total computing resources the execution time per job is limited to 4 hours. We therefore proceed with a restart technique where the model writes up to disk the current state of a large portion of its core memory. Any single job therefore starts with a stage-in phase to bring the restart files and the lateral boundary conditions from the front-end to the proper ES nodes. The model is then launched. Every PE will read its own restart file and then compute for 4 wall clock hours before writing a restart file again. The job ends with a stage-out phase to bring the restart files back to the front-end along with the model output files. Given the fact that the restart files themselves total close to 2Tbytes of data, a single job will take about 10 hours to complete. The waiting period in L queue is highly variable. The extra tropical phase will be completed in May 2005.

We are currently using 4x250 Mbytes hard disks that are traveling back and forth between Japan and Canada to transfer the model output to RPN where a 4-5 Tbytes database is being built. A coarse inspection of the output already revealed significant improvements in the quality and spectrum of the resolved meteorological phenomena. The spinning, tracking and final depth of the system during the tropical phase are all very good. An example of model output is given in fig. 2 for a small window covering the Gulf of Mexico. What really makes this run unique is the fact that the amount of details shown here is in fact globally available on the whole 1km domain – from eastern Pacific to western Europe.

More in-depth data analysis is now about to start and should yield interesting results. In particular an innovative potential vorticity diagnostic tool called Empirical Normal Modes (ENMs) was applied to diagnose inner spiral bands formed in explicitly simulated hurricanes [3]. The ENM method has the capability to decompose simultaneously wind and thermal fields into dynamical consistent and orthogonal modes with respect to wave-activities [4].

For wavenumber one and two anomalies, it was found that the leading modes are vortex Rossby waves that explain 40% to 50% of the wave activity in a period of 24 hours. The Eliassen-Palm (EP) flux and its divergence show that the vortex Rossby waves are concentrated in the inner-core region where the radial gradient of the basic state potential vorticity is large. The vortex Rossby waves show also characteristics typical of flow with critical level and sheared disturbances. Hence these mesovortices are responsible for the dynamical processes controlling the redistribution of angular momentum in the inner core. Laces' results from the 50, 10 and 10 km resolutions will be used to comment the role of these vortex Rossby waves in the tropical and extra-tropical transition phases.

#### 5. Summary

We are very satisfied with the model performance and scalability on a large number of ES' processors. The production phase was completed in about 8 months. A large 4-5 TBytes database is almost complete and diagnostic studies are to start soon. We are now working on a different case study that would allow us to run the same number of grid points but at much higher horizontal resolution. This would again take advantage of the full power of the ES and keep our group at the forefront of the NWP research community.

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## 地球シミュレータを用いた大気の大規模計算: ハリケーンEarlの再現

プロジェクトリーダー

Gilbert Brunet           カナダ気象庁数値予報研究部  
Michel Desgagné       カナダ気象庁数値予報研究部  
大淵    済            海洋研究開発機構 地球シミュレータセンター

著者

Michel Desgagné\*<sup>1</sup>, 大淵    済\*<sup>2</sup>, Gilbert Brunet \*<sup>1</sup>, Peter Yau \*<sup>3</sup>, 古川 祐貴\*<sup>4</sup>,  
Ron McTaggart-Cowan \*<sup>5</sup>, Michel Valin \*<sup>1</sup>

- \*1 カナダ気象庁数値予報研究部
- \*2 海洋研究開発機構 地球シミュレータセンター
- \*3 マギル大学大気海洋科学科
- \*4 東京大学海洋研究所
- \*5 ニューヨーク州立大学オルバニー校

非静力学大気シミュレーション・コードMC2を用いて、ハリケーン Earl の発達過程を再現した。MC2は、地球シミュレータに高度に最適化され、並列化率99.9927%を達成した。Earl のシミュレーションでは、水平解像度50, 10, 1 kmの3重のネステイングを用いている。現在、シミュレーションの結果を詳細に解析しているところである。例えば、陽に表現された台風の内側にあるスパイラル・バンドの渦位を経験的 ノーマル・モードという解析手法を持ちいた力学的解析を行なったところ、卓越するモードの40~50%が渦ロスビー波で説明されることが分かった。このことから、メソ渦が内側のコアの運動量の再分配に重要な役割を果たしていることが示唆される。今後は、他の事例でより高解像度のシミュレーションを行ない、地球シミュレータの能力を最大限に活用して、数値天気予報における最先端の研究を進めていきたい。

キーワード: 地球シミュレータ, ハリケーン・アール, 超高解像度シミュレーション, 台風のライフ・サイクル, 台風の温帯低気圧化と中緯度再発達