Computational Performance Evaluation of a Limited Area Meteorological Model by using the Earth Simulator

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Introduction

The work described in this paper has been done in collaboration with ESC/JAMSTEC (Earth Simulator Center/Japan Agency for Marine-Earth Science and Technology) [1]. CIRA (The Italian Aerospace Research Center) [2] and ESC signed such agreement to study hydro-geological (landslides, floods, etc.) and local meteorological phenomena.
It is well known that meteorological models are computationally demanding and they require both accurate and efficient numerical models on high performance parallel computing. Such needs are strictly and directly related to the high resolution of the model. The interest in this paper is about computational features of the regional version of a non-hydrostatic atmospheric model, currently developed at the ESC by the Multiscale Climate Simulation Project Research Group. In the paper, after a brief description of the model and some implementation details, a description of its parallel performance and scalability analysis on the Earth Simulator supercomputer (ES) is discussed.

1. The global/regional non-hydrostatic atmospheric model

The model is based on non-hydrostatic fully compressible three-dimensional Navier-Stokes equations in flux form; the prognostic variables are density perturbation, pressure perturbation, three components of momentum and temperature [9][10][11].
Equations are casted in spherical coordinates and they are discretized on an Arakawa C/Lorenz grid by using finite difference methods; the grid structure has a horizontal resolution of 5.5 km and 32 levels are used vertically in terrain-following σ-coordinate. A time splitting procedure is applied for fast/slow waves integration in order to improve computational efficiency [3][4][5] following Skamarock-Wicher formulation [6][7]; in particular, it employs Runge Kutta Gill method (2^{nd}, 3^{rd} and 4^{th} order) for advection tendencies (using large time step) and forward/backward scheme for fast modes (using small time step).

In particular, the regional version is nested in a global/larger regional model (coarse grid) by 1-way interactive nesting. A sponge/relaxation boundary condition Davies-like [8] is used to allow the atmospheric interaction between the interior domain (regional domain on fine grid) and the external domain (global/larger regional model on coarse grid). Roughly speaking, the computational domain (fine grid) is composed by a halo area (outside the physical domain) and a sponge area (inside the physical domain); in the first one relaxation values of prognostic variables are defined by interpolation from the coarser grid or by a Newman condition, while in the latter prognostic variables are relaxed. Three types of sponge functions are implemented (hyperbolic, trigonometric and linear).
More details about the model are available in [9].

2. The ES System

The ES is a distributed-memory parallel system made up by 640 NEC SX-6 nodes and each node is a parallel/vectorial shared-memory MIMD (Multiple Instruction Multiple Data) machine having 8 CPUs. The peak performance is about 40 TFLOPS (8GFLOPS per node), the total main memory is of 10 TB and currently it is one of the most powerful supercomputers in the world [12]. The operating system is SUPER-UX, which is based on Unix System V, suitable languages and libraries are provided to achieve high performance parallel computing (FORTRAN90/ES, C++/ES and MPI/ES respectively). In particular, two types of parallelism are available: hybrid and flat. The first one means that parallelism among nodes (inter-node parallelism) is achieved by MPI (Message Passing Interface) or HPF (High Performance Fortran), while in each node (intra-node parallelism) by microtasking or OpenMP. The latter, instead, means that both intra- and inter-node parallelism is archived by HPF or MPI; consequently the ES is viewed as made up by 8x640 processors. Roughly speaking, in the first case a program is subdivided by MPI into *n* threads among nodes and, in each node, the parallelism is performed by OpenMP or microtasking. In the second case a program is subdivided into *n* MPI threads running on *n* processors and the parallelism is performed by MPI.
Detailed description of ES is reported in [1].

3. Implementation Details, and Computational Experiments

The parallel computation of the non-hydrostatic atmospheric model, which has been developed in ESC, is implemented by a hybrid parallelization model: intra- and inter-node parallelisms are performed by micro-tasking and by MPI, respectively. Moreover, such algorithm is based on a SPMD (Single Program Multiple Data) program.
The selected test refers to an intense precipitation event occurred during November 2002 on North-Western of Italy.
To study scalability of the code (performance changing varying problem size or number of processors) experiments have been carried out keeping constant the problem size and varying the number of processors. The sizes along x-, y- and z-direction of the considered computational domains are 600x1152x32, 1200x1152x32 (twice bigger) and 1200x2304x32 (four times bigger). In order to reduce the communication cost a block-wise processors grid is adopted in horizontal for all the performed tests; consequently each processor works on a sub-domain having 32 vertical levels. The number of used processors varies between 16 and 512 (that means 2 and 64 nodes on the ES, respectively); in all cases the step incrementing the number of processors is by powers of two.
The programming language is Fortran90 and to evaluate runtime performance suitable compilation options and environment variables have been set. In particular, the performance analysis tool *ftrace* has been used to collect detailed information on each called procedure (both subroutine and function) [13]; we emphasize that it is better to use this option just for tuning since it causes an overhead. Such collected information is related to elapsed/user/system times, vector instruction execution time, MOPS (million of operations per second), MFLOPS (million of floating-point

operations per second), VLEN (average vector length), Vector Operation Ratio (vector operation rate), MIPS (million of instructions per second) and so on. Criteria to achieve best performance are: vector time has to be close to user time; MFLOPS should be as high as possible; VLEN should be as much as possible close to the vector length (256 on NEC SX-6) because it is the average vector length processed by CPUs (best performance are obtained on longer loops); vector operation rate (%) should be close to 100. Such information has been took into account for each performed experiment.
Scalability has been evaluated in terms of speed-up and efficiency. Since the program cannot be run sequentially, both speed-up and efficiency have been calculated using the elapsed time obtained running the parallel program with the minimum number of processors. In particular, speed-up has been evaluated by Amdhal's Law [15]. Obtained values in all performed tests show a nearby linear speed-up; on the other hand, it has been shown also that efficiency stays always above 70% and the sustained performance is greater than 50% of theoretical peak performance related to the number of used processors.

References

[1] E.S.C. Earth Simulator Center http://www.es.jamstec.go.jp/esc/eng/index.html
[2] C.I.R.A. Italian Aerospace Research Center http://www.cira.it/
[3] J.B. Klemp and R. Wilhelmson (1978) The simulation of three-dimensional convective storm dynamics, J. Atmos. Sci., 35, 1070-1096.
[4]W.C. Skamarok and J.B. Klemp (1992) *The stability of time-split numerical methods for the hydrostatic and the nonhydrostatic elastic equation*, Mon. Wea. Rev. 120, 2109-2127.
[5] W.C. Skamarok and J.B. Klemp (1994) *Efficiency and accuracy of the Klemp-Wilhelmson time-splitting technique*, Mon. Wea. Rev. 122, 2623-2630
[6] W.C. Skamarock and L.J. Wicher (2001) Time-splitting methods for elastic models using forward time schemes, Monthly Weather Review, 130, 2088-2097.
[7] W.C. Skamarock and L.J. Wicher (1998) *A Time-splitting methods for elastic equations incorporating second-order Runge-Kutta time differencing* Monthly Weather Review, 126, 1992-1999.
[8] H.C. Davies (1976) *A Lateral boundary formulation for multi-level prediction models*, Quart. J. R. Met. Soc., 102, 405-408.
[9] K. Takahashi, X. Peng, K. Komine, M. Ohdaira, Y. Abe, T. Sugimura, K. Goto, H. Fuchigami. M. Yamada, K. Watanabe (2004) *Development of Non-hydrostatic Coupled Ocean-Atmosphere Simulation Code on the Earth Simulator* Proceeding of 7th International Conference on High Performance Computing and Grid in Asia Pacific Region, IEEE Computer Society, Ohmiya, 487-495.
[10] K. Takahashi, X. Peng, K. Komine, M. Ohdaira, K. Goto, M. Yamada, H. Fuchigami, T. Sugimura (2005) *Non-hydrostatic atmospheric GCM development and its computational performance*, in "Use of High Performance computing in meteorology", Walter Zwieflhofer and George Mozdzynski Eds., World Scientific, 50-62.
[11] K. Takahashi (2006) *Development of Holistic Climate Simulation codes for a non-hydrostatic atmosphere-ocean couplet system*, Annual Report of the Earth Simulator Center, available at http://www.es.jamstec.go.jp/esc/images/annual2004/index.html
[12] Top 500 web site: http://www.top500.org/
[13] Fortran 90/SX User's Guide
[14] MPI/SX User's Guide
[15] G.M. Amdahl (1967) *Validity of the single-processor approach to achieving large scale computing capabilities* in *AFIPS Conference Proceedings*, 30 (Atlantic City, N.J., Apr. 18-20). AFIPS Press. Reston, Va., 483-485.