Scalability Issues for Wind Simulation using OpenFOAM

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Abstract

The use of the OpenFOAM software for wind simulation over rugged terrain is studied in the paper. OpenFOAM requirements for runtime, virtual memory and disk space are considered using small and medium resolution DEM models for single-process and multi-process cases when running on local workstation and small parallel systems. Based on obtained data, extrapolation of requirements for relatively high resolution models are made and issues concerning the scalability are discussed.

Keywords OpenFOAM, wind simulation, HPC scalability

I. Introduction

The H2020 project VI-SEEM aims at creating a unique Virtual Research Environment (VRE) in Southeast Europe and the Eastern Mediterranean (SEEM), with special focus on the scientific communities of Life Sciences, Climatology and Digital Cultural Heritage [https://vi-seem.eu/]. In this framework one of tasks is to realize wind simulation over rugged terrain, taking as model the mountainous area that includes Albania, undertaken by Polytechnic University of Tirana (UPT). For this purpose the open source OpenFOAM software was selected. The terrain model was obtained from NASA SRTM Digital Elevation Model [USGS archive: https://lta.cr.usgs.gov/]. Experiments were carried out running the software in local workstations and multi-processor systems, aiming at the evaluation of runtime requirements as a preparatory phase for running it in the VI-SEEM VRE. A preliminary literature review showed that the main scalability problems to be expected were dependence from the problem to be solved, model size, inter-process communication, etc. [1 - 13]. In most of the reviewed literature the analysis of scalability was done for concrete problems, without giving details on memory usage, which resulted critical in our experiments confirming the remark of Culpo that “the size of the problems that can be handled on a HPC cluster lies beyond the limitations imposed by smaller in-house clusters” [6].

II. Experimental Setup

Mountainous ranges in Western Balkans are characterized by narrow deep valleys that require high resolution models for wind simulation. Free SRTM DEM that covers Albania is with resolution of 3 arcsec per pixel, which corresponds with a rectangular resolution of 100x100m in equator. We selected a section of DEM of higher resolution available with size 3600x4800 pixel (figure 1). The 3D model size in kilometers was 270x480x10 taking into account the variation of arcsec distances by latitude. In order to test the scalability two other principal models of medium size 360x480 pixels and low size 36x48 pixels were considered. During experiments intermediary models were used as well with sizes is presented in table 1, including the number of digitized elements for each model and requested virtual memory (RAM):

Factor	X size	Y size	Z size	Elements	RAM KB
10	36	48	10	1.73E+04	1.20E+05
30	108	144	30	4.67E+05	4.98E+05
43	154	206	43	1.36E+06	1.25E+06
60	216	288	60	3.73E+06	3.07E+06
100	360	480	100	1.73E+07	1.31E+07
139	500	667	139	4.64E+07	3.34E+07
1000	3600	4800	1000	1.73E+10	1.43E+09

Table 1: Model sizes used for experiments.

SRTM DEM data were transformed in Surfer ASCII arrays using GDAL software [http://www.gdal.org/]. A small program was developed to modify the grid, generated by OpenFOAM module blockMesh, in order to reflect DEM altitudes for the shaping of the relief in the bottom frame of the grid.

Experiments were carried out running OpenFOAM solver for 100 time steps of length 0.1 second, storing results for only 10 times. A time step of 1 second lead to divergence of the process for higher resolution models due to increase of courant number bigger that 1 as result of dis-balancing between spatial and temporal discretization steps [14].

The computer systems used in UPT include a single computer with Intel core i7 and 16 GB of RAM, and a small parallel system (SUGON) based on Intel Xeon E5506 processors but with only 2GB RAM; the operating system is Linux Fedora 20 in desktop and Scientific Linux 6.7 in the SUGON. Further systems to experiment with include an HPC Cluster with non-blocking DDR Infiniband with 36 nodes with dual Intel(R) Xeon(R) CPU X5560 @ 2.80GHz; and 24 GB RAM; and the supercomputer system Avitohol (https://www.top500.org/system/178609) with 150 servers with dual Intel Xeon E5-2650v2 8C @2.6GHz; both in Institute Of Information And Communication Technologies - Bulgarian Academy Of Sciences (IICT-BAS).

III. Preliminary Simulation Results

SRTM DEM data are presented in figure **??**. The area of study includes Albania, and parts of Montenegro, Kosovo, Macedonia and Greece (figure 2). The area is characterised by a group of high mountains in North - Alps, and several ranges of mountains that extend in direction North-North-West - South-South-East. Only about 1/3 of the territory of Albania is lowlands, the so called Pre-Adriatic Depression. Narrow valleys have their impact in wind flows.

The 3D prismatic layer area of thickness 10km was digitized that resulted as output of blockMesh module was deformed modifying Z coordinates of all nodes, obtaining the shape of the terrain in the bottom face of the prism as in figure 2.

Examples from execution of the model with linear size factor 100 are presented hereunder. Simulation was done for boundary conditions with fixed potentials of value 0 and 1 in southern and northern faces respectively that give a wind flow North - to - South. Simulation images are obtained using ParaView software for the velocity U in altitude of 1000m.

The North - South velocity of wind flow in altitude 1000m is presented in figure 3. Gray areas represent mountain altitudes over 1000m. A near to surface slowness of the wind is visible around mountain picks. The effect of the relief is more visible in following images representing West - East and vertical wind flows.

Due to oblique extension of mountain ranges, in all valleys there is generated a component of West - East wind flow with magnitude 50% in the altitude 1000m (figure 4). At the

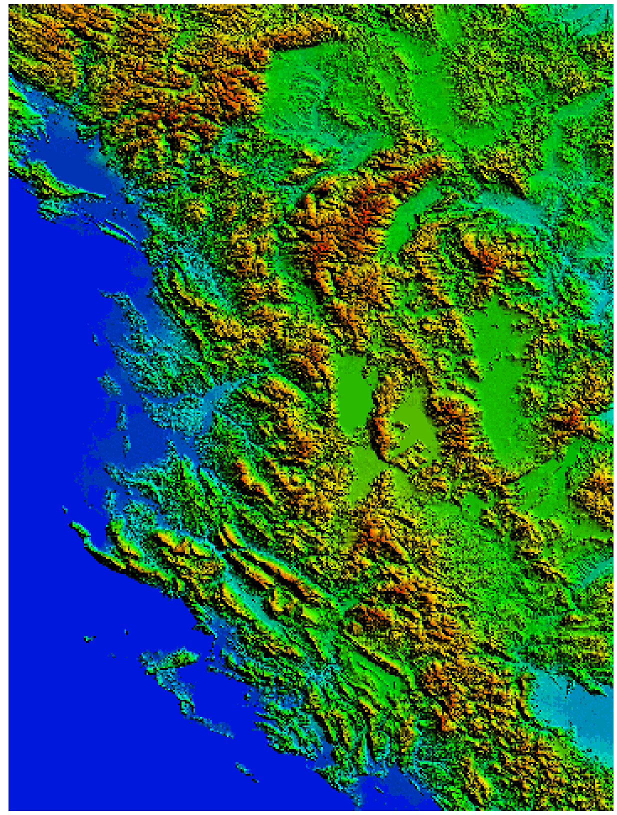

Figure 1: DEM image for Albania and surrounding area.

same time "protected" valleys where this wind has only a magnitude 25% are identified,

The vertical flow of the wind in altitude 1000m reaches high velocities in some of mountain slopes (figure 5). This phenomenon is significant in two areas - northern boundaries of Mirdita and mountainous areas East of Vlora city.

Such results are important for planning of setup of wind energy farms, and for air transport. A more complete analysis is planned for the future work.

IV. OpenFOAM Scalability Results

The execution of OpenFOAM suite in single-process mode requires the run of the mesh generator blockMesh, followed by the solver âĂŞ in our case icoFoam. After the solver the other modules like ParaView may be used for the visualization of results. While the mesh generator and the solver may be run remotely through ssh sessions, for a remote visualization of results it is necessary to use ParaView in client-server mode. In case of MPI parallel run of the solver two other

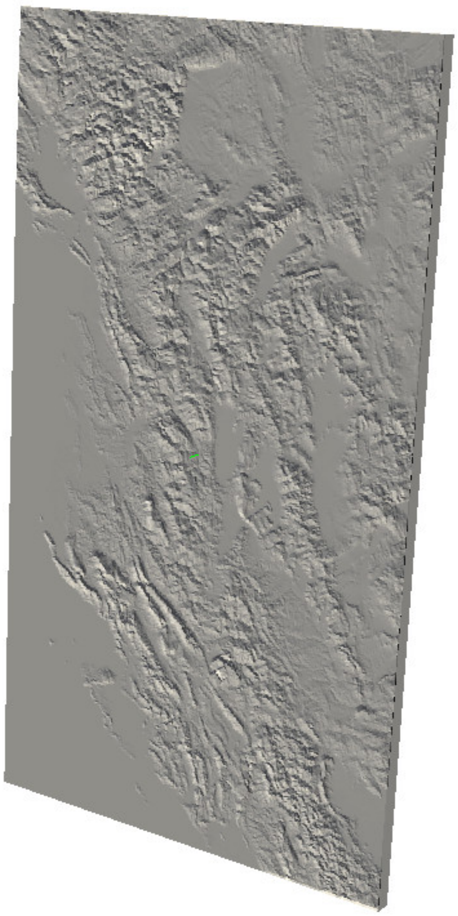

Figure 2: Bottom surface of 3D volume deformed based on DEM.

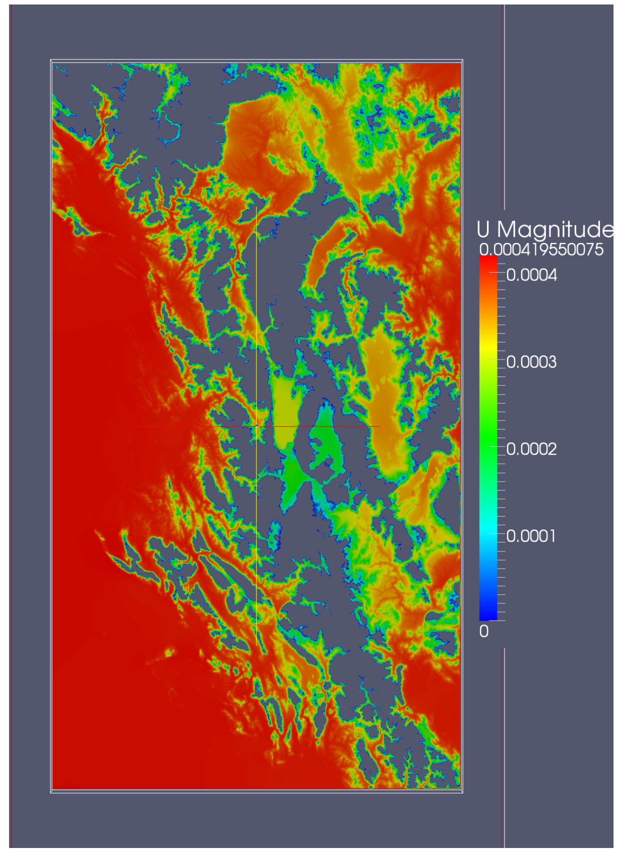

Figure 3: North-South wind flow in altitude 1000m.

OpenFOAM modules are needed for the decomposing of the mesh in fragments for each process, and the combination of fragmented results in a single set.

Initial data for the OpenFOAM are not voluminous, they include text files for different physical and temporal parameters, coordinates of basic blocks of the area and respective faces. The module blockMesh generates huge text files with coordinates of each node and nodes for each face. This data is used as input for the solver that generates, for different time slots in respective directories, text files with values of the potential "p" per node, also the velocity "U" and flux "phi" for each face.

The decomposing module generates text files with coordinates of nodes and nodes of faces for each MPI process, and solver processes generate their results in separate directories. After the reconstruction there is significant redundancy of data in the disk. Also the evaluation of required disk space is dependent of the number of time slots recorded.

This schema of exploitation of OpenFOAM as described above was considered during the experiments, through evaluation of both memory, disk and CPU requirements of different modules. Virtual memory was considered for requirements in central memory - tests with big models in computers with small central memory showed bad performances due to loss of time during swapping. The Linux command "top" was used to evaluate the size of virtual memory.

We succeeded to run two principal models of low and medium resolution in the local computer, obtaining first evaluations for virtual memory and disk data volumes, presented in figure 6.

The order of virtual memory requirements resulted at the range O(N^2), while for the disk space O(N^3), where N is the number of nodes in one linear edge of the 3D digitized area. The medium sized model of 360x480 points was run in the local computer with 16GB RAM, but could not

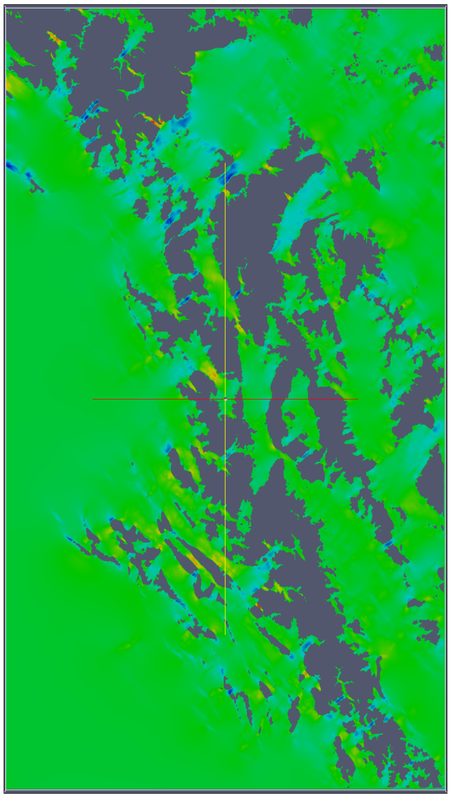

Figure 4: Induced West-East wind flow in altitude 1000m.

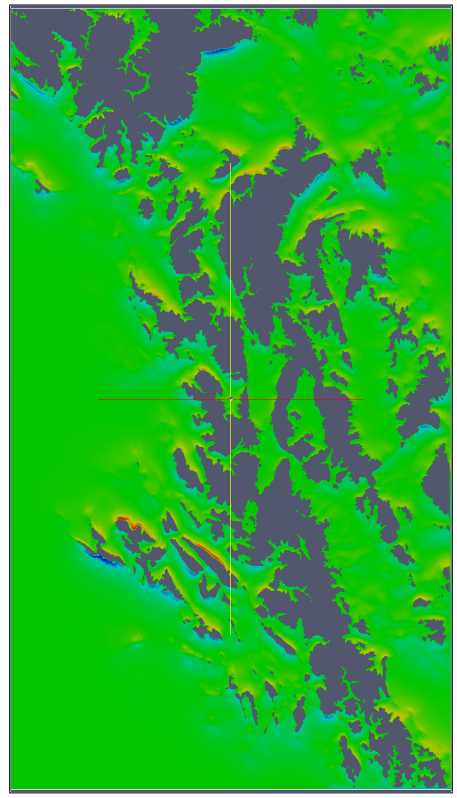

Figure 5: Induced vertical wind flow in altitude 1000m.

run in the parallel system SUGON due to the small central memory and swap space that were half of required virtual memory. Running the high resolution model simulation as single process for the DEM with 3600x4800 points (the factor 1000) may require a system with central memory of the range 2,000 GB; lesser memory would increase significantly the runtime due to disk swapping.

In case of multi-process execution of OpenFOAM solver we obtained another view of virtual memory requirements presented in figure 7. An asymptotic tendency is observed towards the level of 1 GB of virtual memory (memory evaluation for the high resolution model, the factor 1000, is due to extrapolation).

The parallel MPI runtime was evaluated in the HPC parallel system in IICT-BS in Sofia using statistics from the Linux command /usr/bin/time.

We considered a single process runtime for all OpenFOAM modules - blockMesh, icoFoam, decompose and reconstruct for digitizing of the area, running of the solver, decomposing the data for multi-process MPI run and recomposing results respectively (figure 8).

Except the solver icoFoam, other modules have similar runtimes and have to be run in single-process; this cannot be done in small systems even if MPI processes would require less virtual memory: even splitting each MPI process in a separate node to use the full central memory, preparatory tasks must run in a single node.

For the icoFoam solver, 4 processes and 8 processes runs were tested in a single node and also splitting processes in two nodes (figure 9). This permitted a first evaluation of the difference between inter-process BUS communication within a single node versus LAN communication between processes in different nodes, which was evaluated as negligible.

An important observation was the fact that the scalability of runtime when jumping from 4 processes to 8 processes was degenerated (figure 10), indicating that the increase of the number of processes in HPC may not lead to expected reduction of runtime.

Further tests in bigger systems like the supercomputer system Avitohol are expected to give better performances

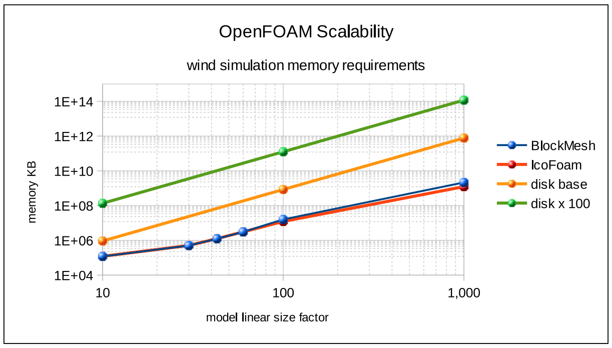

Figure 6: Memory usage of OpenFOAM - single process run.

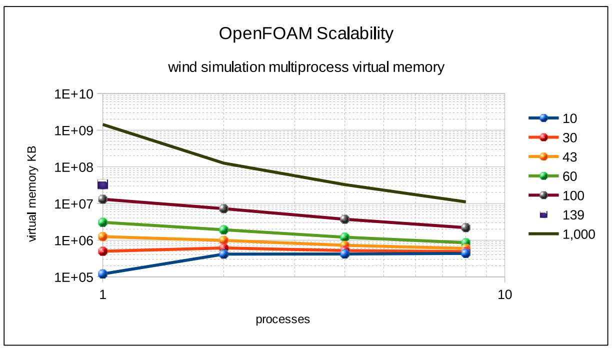

Figure 7: Memory usage of OpenFOAM - multi process run.

and more realistic evaluation of memory and CPU requirements, necessary for running of big models in VI-SEEM VRE infrastructure.

V. Conclusions

Usage of OpenFOAM for wind simulation over rugged mountainous terrain of Albania and surrounding area resulted problematic in small parallel systems. Volume of requested virtual memory reached levels of 10-30 GB for medium sized models, which resulted higher than central memory causing degradation of the runtime scalability. Even when central memory is sufficient, increasing of number of processes lead to degradation of scalability. Actually the optimal runtime for medium sized models was obtained for 4 processes only.

Considering the high resolution model, an extrapolation of runtime gave the value on range of 10,000,000 seconds (3,000 hours) with 2,000 GB virtual memory. Only supercomputer systems like Avitohol may offer such resources. It is also

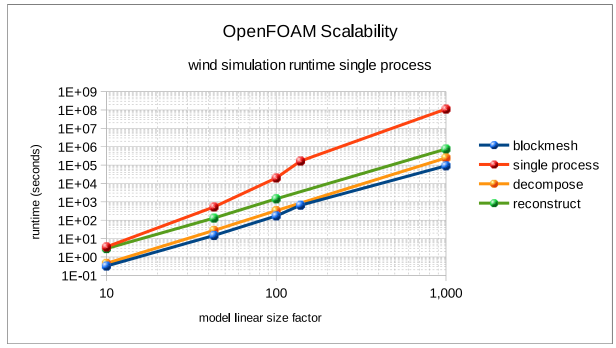

Figure 8: OpenFOAM runtime - single process run.

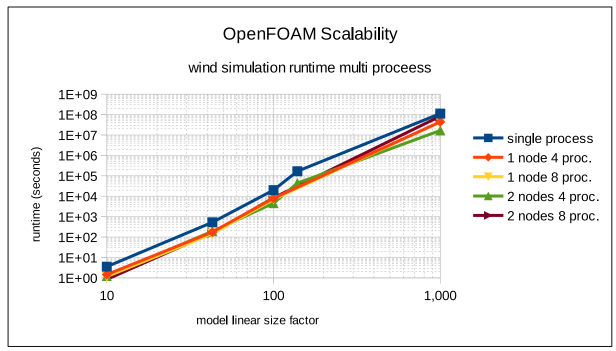

Figure 9: OpenFOAM runtime - multi process run.

necessary to consider that for the study of turbulences and eddies, it would require the storage in disk of a greater number of time slots, compared with experiment setup presented in this paper.

Multi-process execution of OpenFOAM solver may require much less virtual memory for higher number of processes but auxiliary calculations for mesh generation, decomposing the data for each process and recomposing results apparently cannot be run as multi-process, requiring the full central memory capacity.

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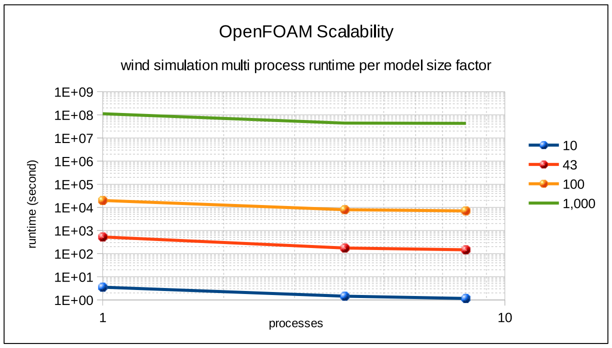

Figure 10: OpenFOAM runtime - multi process run.

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