ON CONVERGENCE OF WIND SIMULATION OVER RUGGED TERRAIN USING OpenFOAM

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ABSTRACT

Simulation of air wind flows over mountainous terrain is important for both environmental and green energy studies. We have experimented OpenFOAM software for this purpose, considering that the two-thirds territory of Albania is mountainous with narrow valleys with northwest – southeast extension. The work started within the VI-SEEM [https://vi-seem.eu/], a European H2020 project, where the scalability of the software was studied. The present paper reports further results throwing light on convergence of the software when turbulence is considered. Final results showed that very fine temporal discretization is necessary for the iterative process of turbulence model over mountainous terrain to stay convergent for a temporal period of at least one hour, necessary for the magnitude of air flows to reach relative stable values, compared with the convergence of the air flow in flat terrain case.
Keywords: convergence, OpeanFOAM software, wind, simulation

1. INTRODUCTION

Air flow simulations are presented in numerous published works, but due to the numerous applications most of papers deal with very specific cases. In (Lombardi *et al*., 2011) the dynamics of sailing boats is analyzed, (Lysenko *et al.*, 2014; Ravelli *et al*., 2014) deal with air flows in turbine constructions, while (Kornyei 2012) analyses gas flows in combustion chambers, (Ponweiser *et al*., 2013) deal with airflow issues for aircraft design, while (Sidlof and Ridky 2015) evaluated the scalability of the parallel CFD simulations of flow past a fluttering airfoil.

Results on the scalability of OpenFOAM are found in (Rivera *et al*., 2011), dedicated to large eddy simulations. Interesting results are presented by (Culpo 2010), who clearly declared the difficulty of solving 3D airflow simulations in modest HPC systems. Dord *et al*., (2010) investigated the performance of OpenFOAM.

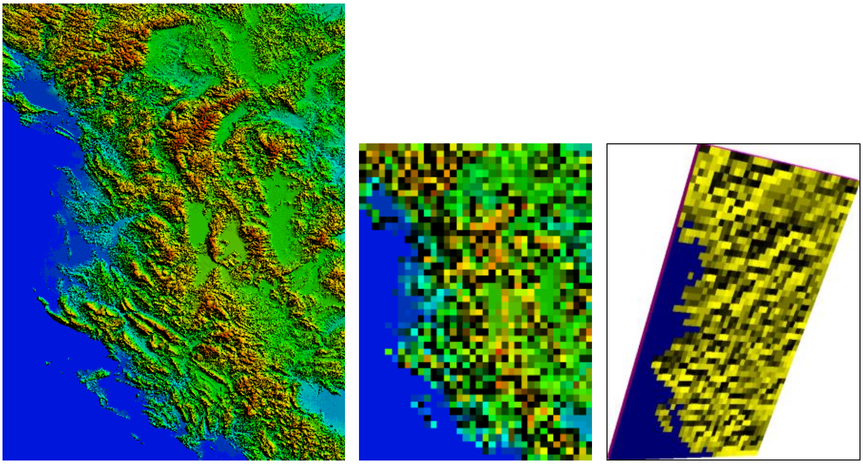
Tapia (2009) made a general analysis of wind flow over complex terrain. Flores *et al.*, (2013) have simulated wind turbulence over complex geometry as hills and urban areas. (Han et al., 2016) investigate the role of the atmospheric boundary layer in both flat and complex terrains.

Results given in the literature show that concrete geometric complexity of the ground surface plays an important role in the scalability and quality of wind simulation, which is difficult to be achieved in modest HPC systems. We used a low resolution DEM of the terrain for our simulations in the small HPC system available at the Faculty of Information Technology of the Polytechnic University of Tirana, Albania. Previous results presented in (Frasheri and Atanassov 2016; 2017; 2018) demonstrated that 3D modelling of wind over mountainous terrain with OpenFOAM is time consuming and requires huge RAM capacities for worknodes of the parallel system. Increase of time span for the iterative process was limited by the temporal step discretization, which impacted the values of courant number leading to the divergence of solutions.

The courant number reflects the ratio between temporal and partial discretization steps, when spatial step becomes so small that the mass of fluid moves over a whole spatial element in one-time step, such condition leads on the divergence of the process and the software stops. All previous tests were done with different spatial discretization resolution keeping the same time span for the iterative process. In the present investigation, we tried to increase gradually both the time span of iterations and related time step, in order to understand better the link between divergence due to increase of courant number and limits of time span of iterations.

2. MATERIALS AND METHODS

We used a terrain model of the territory of Albania based on the DEM data from USGS repository [USGS archive: https://lta.cr.usgs.gov/], for a section of 360x480 km digitized as image with 36x48 pixel, with low resolution of 10 km/pixel. The 3D model of atmosphere was defined with dimensions 360x480x10 km digitized by 36x48x10 elements:



DEM model 360 x 480 km model 36x48 pixel oblique view of 3D model

Fig. 1: SRTM DEM model of terrain, reduced model and its oblique view for OpenFOAM.

Boundary conditions were defined as:

- northern face with potential +1.0
- southern face with potential -1.0
- bottom face with velocity magnitude zero
- left, right and top faces with normal gradient zero

OpenFOAM solver used was **piso** for incompressible turbulent cases, using Reynolds number 1.0e-5. Temporal digitizing of the 3D model for different duration of iterative process (time values signed with 'F' are for the flat model) are given in the table:

Time (seconds)	Step (seconds)	Time (seconds)	Step (seconds)	Time (seconds)	Step (seconds)
10	0.01	20,000	20	300,000	100
20	0.02	30,000	30	400,000	100
50	0.05	40,000	40	400,000	1
100	0.1	60,000	60	500,000	1
500	0.5	100,000	100	500,000 F	1
1,000	1	150,000	100	700,000 F	1
5,000	5	150,000	150	1,000,000 F	1
10,000	10	200,000	200	2,000,000 F	1
15,000	15	200,000	100	5,000,000 F	1

For duration up to 200,000 sec the time step was increased up to 200 seconds in proportion using 1,000 iterations, increasing the time span. For longer duration the time step was reduced firstly to 100 seconds and down to 1 second.

Calculations were done using the parallel system of Faculty of Information Technology, Polytechnic University of Tirana, based on Intel ® Xeon ® E5506 processors running Scientific Linux 6.7, OpenFoam 2.3 and ParaView-3.12.

Computational results

Convergence of iterative process is expressed through the courant number that should be less than 1.0. For the rugged model using time step of 1 second, time span lasted up to $5x10^5$ sec and solution diverged with strong oscillations of courant number jumping up to 10^6. While for the flat model time span was extended until $5x10^6$ seconds without sign of divergence, with courant number converging asymptotically towards the value $3x10^6$ (Figure 2).

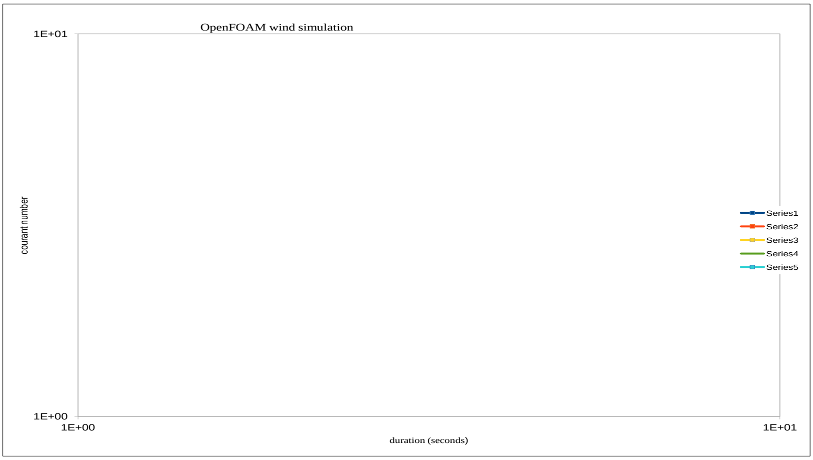


Fig. 2: Divergence of courant number.

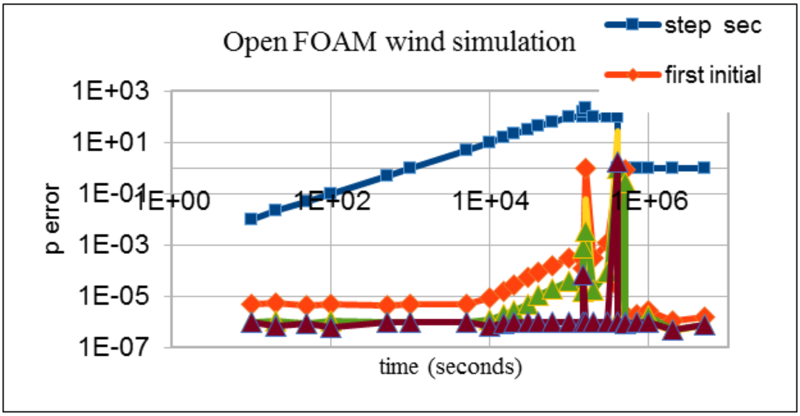


Fig. 3: Variation of P field errors.

The variation of errors for the field P for all models has spikes up to 1.0 related with the divergence in cases of time span 200,000 and 400,000 seconds, while continuation of flat model remains oscillated around the value 10^{-6} (Figure 3).

Minimal and maximal magnitude for field U for rugged models increased continuously until divergence spices visible in 400,000 seconds; while for flat models converge towards value range 2.0 – 4.0 (Figure 4).

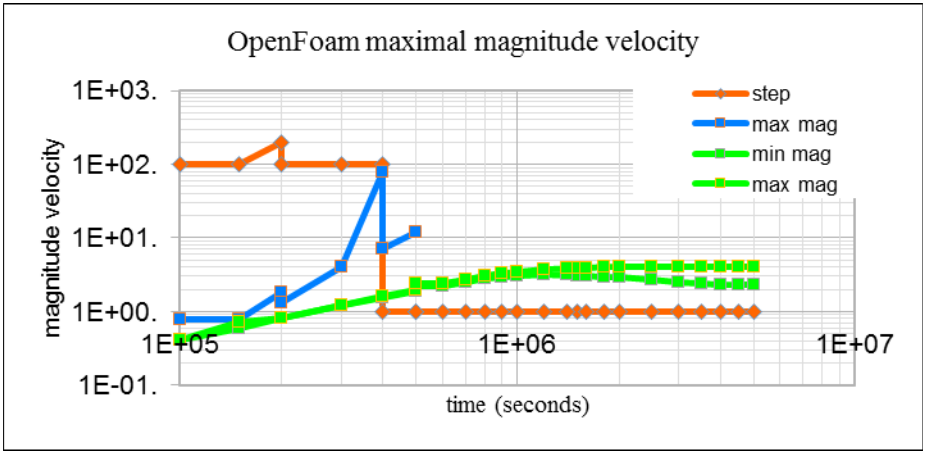


Fig.4: Variation of U field values.

Runtime remains constant for solutions with duration up to 10^5 seconds, when the same number of iterations was used through variation of time step.

For solutions with longer duration runtime increases as result of increasing number of iterations using the same time step of 1.0 seconds (Figure 5).

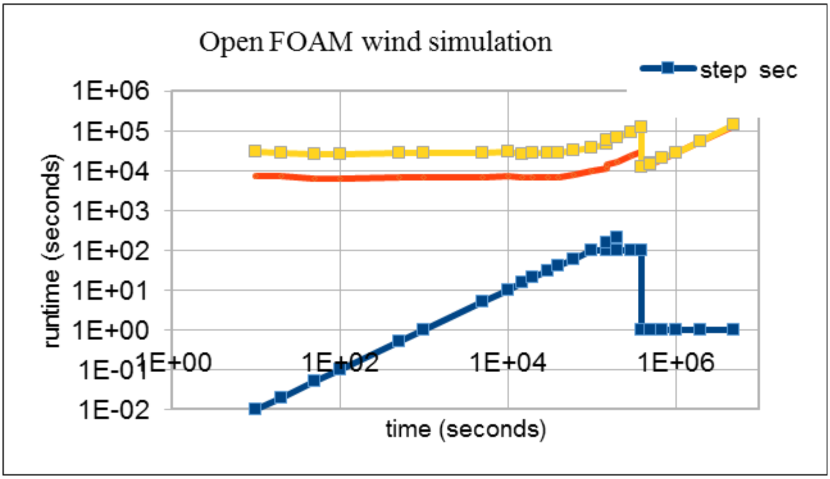


Fig. 5: Variation of runtime.

Variation of solutions for the rugged model is presented for the altitude 1,500m and 5,000m. Typical case is for divergent case of duration $4x10^5$ sec with time step 1 sec, where in final seconds there is emergence of extra high values of wind velocity magnitude in northern mountainous section (the red spot, because of these high values of the magnitude the variations of the rest of the field are not visible). Turbulence signs are visible for wind flows at altitude 5,000m (Figure 6).

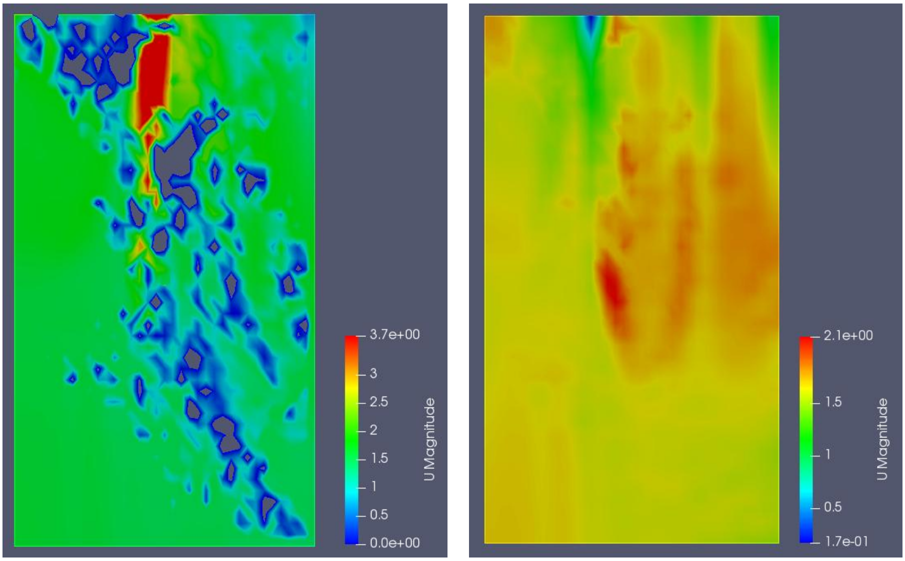


Fig. 6: Deformation of solution after 4x105sec in altitude 1,500 m and 5,000 m.

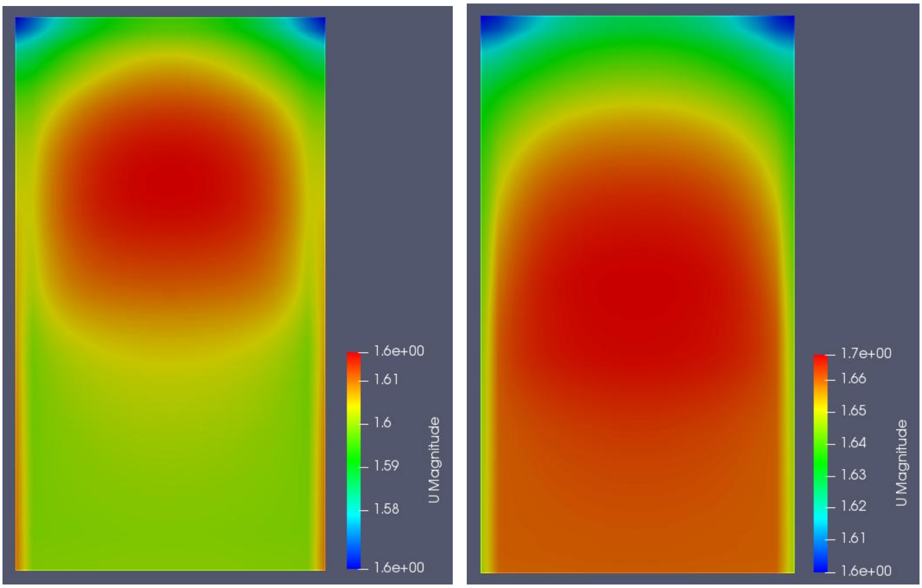
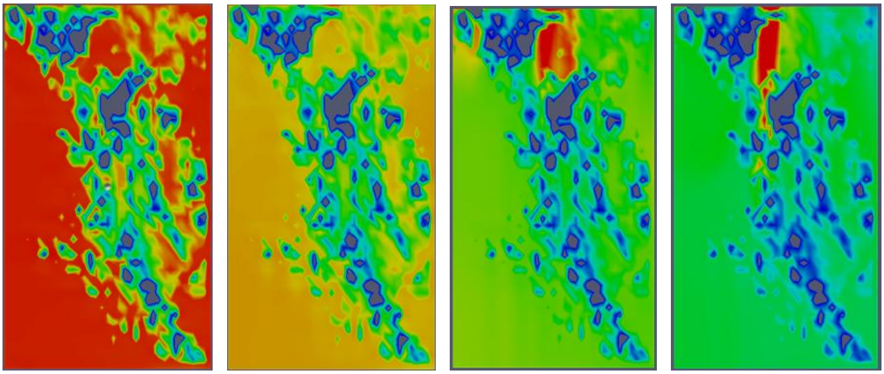


Fig. 7: Flat solution in $4x10^5$ sec in altitude 1,500 m and 5,000 m.

Solution of the flat model for altitude 1,500 m and 5,000 m and time $4x10^5$ sec with time step 1.0 sec showed no signs of anomalous and turbulence values (Figure 7).

Suite of turbulent solutions of rugged model in altitude 1,500m and 5,000m and time step 1 sec for moments of time from $2.0x10^5$ up to $4.0x10^5$ seconds is presented in the Figure 8 depicted (each of images tagged with minimal and maximal magnitude values).

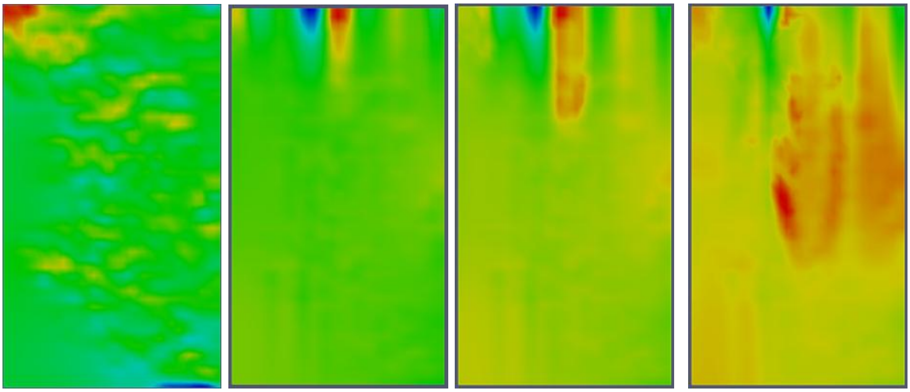


0.0000-0.2110 0.0000-0.7700 0.0000-1.9000 0.0000-3.7000

Fig. 8: Rugged solution in altitude 1,500 (magnitude scale relative with each image).

In first images related with the altitude 1,500m, only the decrease of wind speed magnitude is visible near ground surface around mountain pics. Gradually the anomaly in northern part of the area appears; because of the used linear color scale variations of magnitude in the rest of area are not visible.

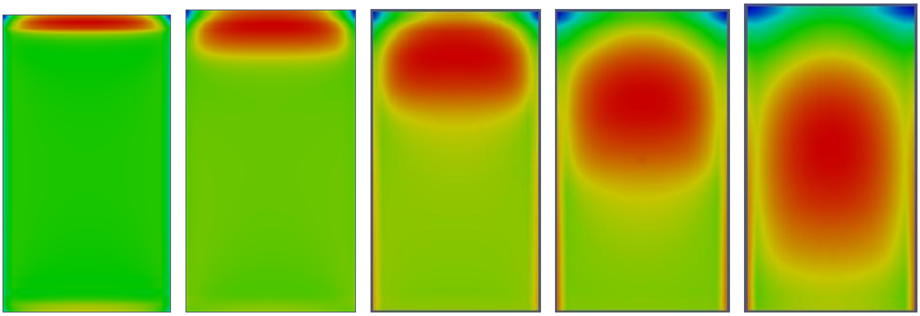
For the altitude 5,000m the first images show a relatively uniform magnitude distribution, except the northern part where both anomalous minimal and maximal magnitudes are visible, generated from mountain pics in Montenegro. Only in final images there are turbulence visible due to divergence of the solution (Figure 9).



0.2000-0.2153 0.5800-1.3300 0.4200-1.6200 0.1700-2.1000

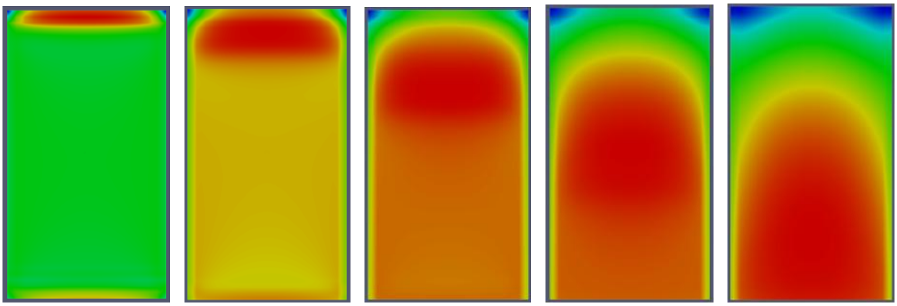
Fig. 9: Rugged solution in altitude 5,000m (magnitude scale relative with each image).

In all these images the maximum of color scale is defined manually for a clearer view of magnitude variations. Figure 10 and 11 depict the suite of turbulent solutions in flat model altitude 1,500m and 5,000m and time step 1 sec for moments from $5x10^4$ seconds up to $5x10^5$ seconds. In both altitudes the solution indicates a wind transport phenomenon starting from the north moving towards the south.



0.4115-0.4145 0.8100-0.8223 1.1995-1.2230 1.5650-1.6150 1.9180-1.9970

Fig. 10: Flat solution in altitude 1,500m (magnitude scale relative with each image).



0.4150-0.4182 0.8220-0.8360 1.2150-1.2550 1.6000-1.6700 1.9600-2.0700

Fig. 11: Flat solution in altitude 5,000 m (magnitude scale relative with each image).

3. CONCLUSIONS

Simulation of turbulent wind flows over mountainous terrain in regional scale resulted difficult when OpenFOAM was used in models HPC systems, confirming the conclusion of Culpo. Considering the spatial extension of the territory, for high winds of 30 km/sec the mass of air needs about 10 hours to move over the whole territory, characterized by narrow valleys of few hundred meters wide. In order to obtain solutions for time span of several hours such terrain with narrow valleys, increase of model's spatial resolution requires proportional increase of temporal resolution in order to keep the courant number under the divergence level of 1.0, implying both computational resources in central memory of worknodes and in runtime. Extension of temporal duration also requires reduction of time step in order to avoid the divergence of solution. All this implies the need for ultra-scale computing facilities for territorial high resolution solutions for engineering purposes.

More complex boundary conditions are necessary in order to obtain correct solution of wind magnitude distribution in regional scale. Inclusion of convection flows due to temperature differences must be considered as well. Detailed solutions useful for engineering works may be obtained starting with low resolution regional models and using its solutions as boundary conditions for localized solutions of high resolution.

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