SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Aerodynamic response of precipitation gauges immersed in a turbulent wind field
Computer Project Account:	spitlanz
Start Year - End Year :	2015 - 2015
Principal Investigator(s)	Prof. Luca G. Lanza
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Other Researchers (Name/Affiliation):	Matteo Colli, University of Genova

June 2016

Summary of project objectives

(10 lines max)

The objective of the project is to compute time dependent runs of a numerical model of the 3D airflow field around a common un-shielded precipitation gauge, obtained by imposing a turbulent free-stream airflow (simulating wind with an averaged horizontal speed lower than 10 m/s) and by modelling its aero-dynamic response under a Large Eddies Simulation (LES) turbulence approach.

The simulation of sufficiently refined LES airflows to solve the spatial and temporal scales of the hydrometeors motion near the precipitation gauge represents a fundamental tool for the development of accurate and innovative correction methodologies of the snowfall/rainfall measurements.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

In the first part of this project, we focused on preparatory activities to set-up the Computational Fluid Dynamics (CFD) model, which is the objective of this special project. The analysis of high-frequency 3D anemometer measurements from the field in order to accurately define the inlet boundary conditions was completed during summer 2015.

The spatial discretization of the computational domain was another task that took several months for its completion. The optimization of the mesh has the objective to balance the LES requirement of fine grid spacing with respect to the total amount of cells, which have a direct impact on the number of parallel jobs necessary to run the simulation.

The importance of these activities were crucial considering the large hardware requirements of the Large Eddy Simulation in a complex spatial domain. In fact, all the SBUs allocated to run the turbulent model were dedicated to achieve a fully developed solution of one single simulation run (one mean wind speed) performed in December 2015.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The researchers involved in the *spitlanz* special project found a clear and well-structured application process. The principal investigator has been promptly informed about the result of the proposal.

Furthermore, the investigators received a responsive and comprehensive support from the ECMWF staff related to technical aspects such as the access to the High Performance Computing Facility, the hardware resources accounting and the execution of the numerical activities.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

The *spitlanz* special project achieved the result of simulating a time dependent fully turbulent three-dimensional airflow around a common un-shielded precipitation gauge by means of advanced Computation Fluid-Dynamic (CFD) techniques. Given the massive hardware requirements of the Large Eddy Simulation (LES) model, the goals of this activity was achieved by performing two single runs that corresponded to 20 seconds of physical time. In order to perform a comparative analysis, the first run was performed without inducing turbulence in the free-stream airflow while the second run included a free-stream turbulence intensity measured in the field.

The activity carried out during the first part of the project was focused on the set-up of a time-dependent finite volume simulation that constitutes the objective of this special project. As a first step of the work, we collected air velocity measurements made at the precipitation gauge level by using a high-frequency 3D anemometer. The data sets were then used to obtain information on the turbulence occurring under operational conditions at the gauge collector. Table 1 shows the values of the time averaged wind speed components, the turbulent kinetic energy and the turbulent intensity computed for two 15-min long time series observed at the Nafferton Farm field site in UK.

Tab. 1: *Kinematic characteristics of the high-frequency 3D air velocity measurements performed at the Nafferton Farm (UK) field site*

Time series	**Duration** *(min)*	**Sampling Frequency** *(Hz)*	**Average wind speed (Uw_x, Uw_y, Uw_z)** *(m/s)*	**Turbulent Kinetic Energy** *(m^2/s^2)*	**Turbulent Intensity** *(-)*
#1	15	20	(0.05, -2.23, -0.02)	0.39	0.22
#2	15	20	(0.39, -2.74, 0.00)	0.45	0.19

The same time structure of the airflow turbulent fluctuations observed infield constitutes the inlet boundary condition of the CFD simulation. Fig. 1 reports the instantaneous values of the wind speed and the horizontal wind direction for time series #1. By performing the common separation of the velocity terms into the time-averaged and the fluctuating components, it is possible to represent the turbulence of time series #1 as shown in Fig. 2.

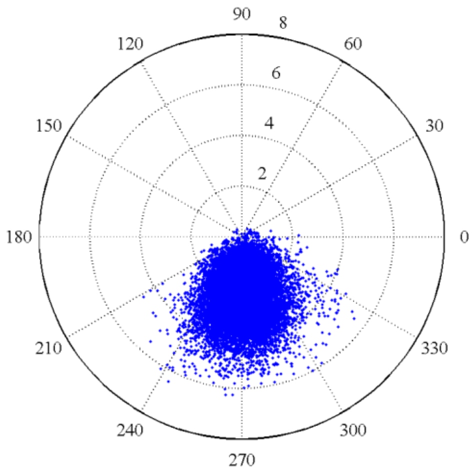

Fig. 1: *Polar plot of the high-frequency 3D anemometer measurements on a horizontal plane performed at the Nafferton Farm (UK) field site. The radius represents the wind speed (m/s) while the angle is the wind direction on the horizontal plane.*

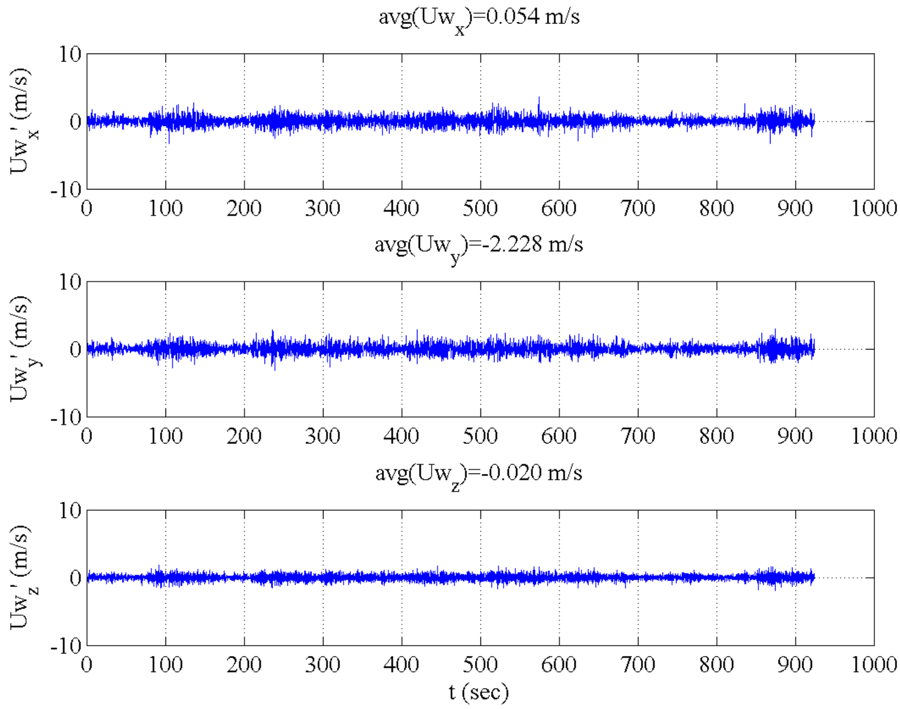

Fig. 2: *Time series of the fluctuating wind velocity components U_w'(m/s) measured by an high-frequency 3D anemometer at the Nafferton Farm (UK) field site.*

The field data showed that a free-stream airflow characterized by an average speed between 2 and 3 *m/s* and measured at the level of the precipitation gauge collector has a turbulent kinetic energy value $TKE \approx 0.4$ m^2/s^2 corresponding to a turbulent intensity approximated to 0.2. These are the main kinematic characteristics of the airflow at the inlet of the simulation environmental box. The synthetic reconstruction of the time and spatial structure of the velocity field on the inlet boundary according to the previous parameters is currently ongoing.

Simultaneously to the analysis of high frequency airflow observations, the first months have been dedicated to the realization of the spatial domain grid (mesh).

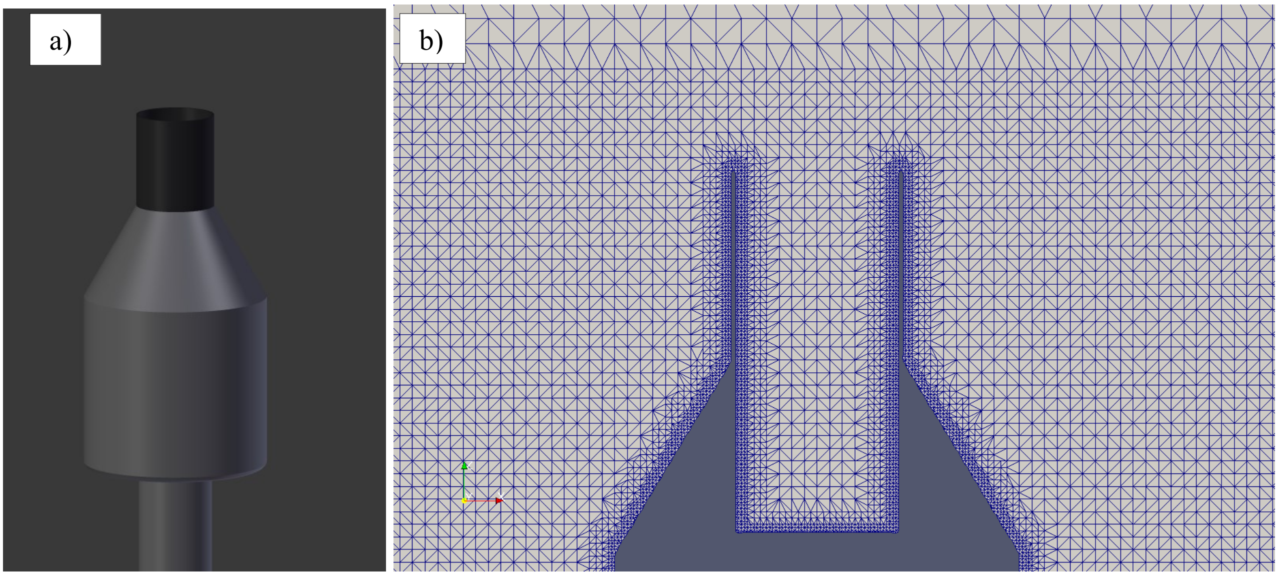

Fig. 3: *3D model of a common unshielded precipitation gauge geometry (panel a). Spatial discretization grid based on polyhedral cells (panel b) on a vertical plane passing through the gauge center.*

Panel *a* of Figure 3 reports a three-dimensional representation of the axial-symmetric precipitation gauge geometry. The gauge surfaces are surrounded by the finite volumes cells that compose the spatial grid of the computational domain. Increasing refinement levels of the mesh have been imposed by getting closer to the gauge surfaces (no slip wall conditions) as shown in panel *b*. The illustration focuses on a vertical plane passing through the gauge center.

In addition, three vertical columns were added upstream the gauge to introduce an aerodynamic obstacle aimed at generating an isotropic air turbulence in the wake. The investigators pursued this strategy to simulate a turbulence intensity that is comparable to the observations from the field reported in Table 1.

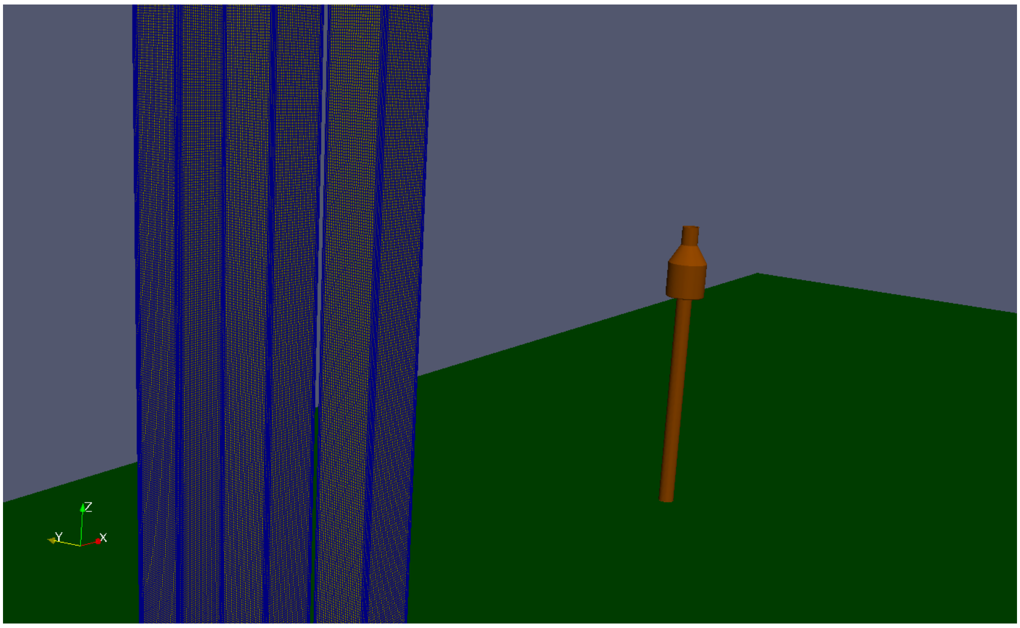

Fig. 4: *3D view of the gauge model and the upwind column used to generate turbulence.*

Two different meshing techniques were compared: hybrid tetrahedral/prism mesh and hexahedral mesh. The computation of the spatial grid has been performed by using algorithms optimized for the execution in 32 parallel threads.

Tab. 2: *Geometric characteristics and quality factors of different tested grids.*

Mesh	*N. elements*				*Max values*		
	tetrahedral	*prims*	*hexahedral*	*polyhedral*	*skewness*	*non-orthog.*	*aspect ratio*
#1 URANS	1.5 10^6	4.7 10^6	0	0	2.7	67.4	84.5
#2 LES	5.5 10^6	22.0 10^6	0	0	2.7	67.3	161.3
#3 LES	0	7.2 10^4	6.9 10^6	0.5 10^6	1.2	31.3	3.5

Table 2 shows the number of elements resulting from the different spatial gridding and the associated geometric quality factors of the finite volumes constituting the mesh. The result of this step of the project is a hexahedral mesh constituted by 7.5 million cells characterized by low maximum values of skewness, non-orthogonality and aspect ratios. In particular, the three quality factors of mesh #3 (Table 2) always show lower values than those resulting by adopting hybrid tetrahedral/prism grids under the same level of refinements around the surfaces of the precipitation gauge. As a consequence, the URANS and LES simulations performed in the following stages of the project were based on hexahedral/polyhedral spatial discretization.

Preliminary tests were conducted to evaluate the best distance between the gauge and the three columns aiming at achieving the desired turbulent kinetic energy k and the mean horizontal wind speed U_w of Table 1 by means of a URANS model executed locally by the investigators. Figure 5 reports about the spatial distribution of the turbulence kinetic energy for a generic instant of the time-dependent solution and Figure 6 shows the time history of k samples at different stream-wise distance from the three columns. The results of this preparatory CFD study are the following set of conditions adopted to set-up the large LES simulations executed on the ECMWF High Performance Computing facility:

- Columns-gauge stream-wise distance equal to 9 m
- Horizontal wind speed at the inlet boundary (constant profile) equal to 6 m/s
- Turbulent kinetic energy at the inlet boundary equal to 0.01 m^2/s^2

and providing the following effects at the gauge location:

- Air velocity magnitude $\approx$ 3 m/s
- Turbulent kinetic energy $\approx$ 0.46 m^2/s^2

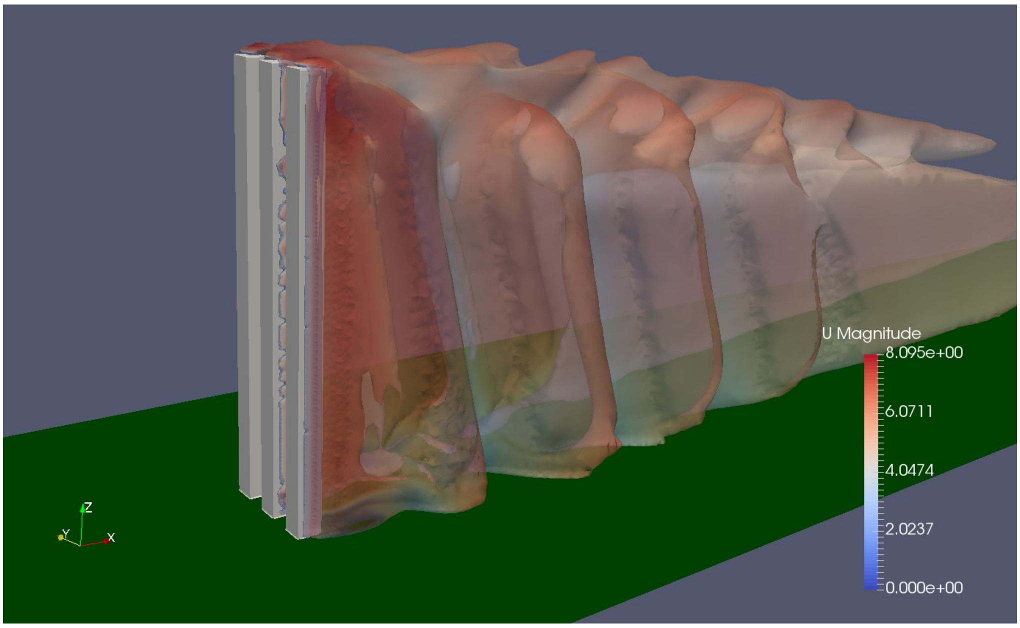

Fig. 5: *Contours of the turbulence kinetic energy k=0.6 m^2/s^2 field generated by the three columns under a free stream wind speed U_w equal to 6 m/s (URANS simulation results).*

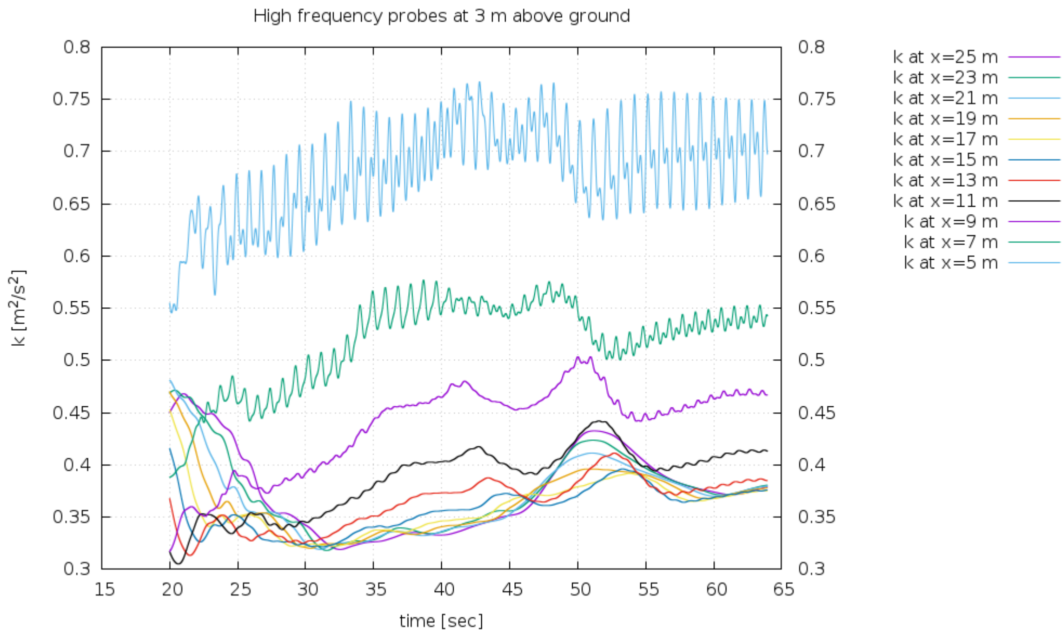

Fig. 6: *Time series of the turbulent kinetic energy k at difference stream-wise distance from the three columns U_w = 6 m/s (URANS simulations).*

On the basis of these results, two different spatial grids have been prepared. The first is composed by the environmental box containing the precipitation gauge geometry, while the second grid also included the three upstream columns used to induce turbulence. This approach allowed performing a comparison between the gauge aero-dynamics in case of laminar and turbulent flow.

The following step of the activity was to transfer the two LES simulation set-ups (mainly composed of the boundary condition algorithms and the three dimensional spatial grid) on the ECMWF computing system and to perform high-resolution time-dependent simulations.

Both the simulations where performed successfully in terms of numerical residual errors and investigated time (20 seconds). A run-time processing of the air velocity U and pressure p fields was adopted to reduce the amount of data stored in the database and transferred to the investigators storage machines. In particular, the velocity and pressure fields have been time-averaged starting from the 15th second and the oscillating components has been stored separately to evaluate the turbulence intensity in a post-processing stage. A set of virtual probes has been added to the simulation set-up to perform a high-frequency sampling of the physical variables at fixed locations around the gauge collector.

The analysis of the LES simulation results is currently under progress but Figures 7 and 8 provide an anticipation of the mean air velocity figures observed around the gauge with and without the free-stream turbulence. The two panels show the vertical component of the mean air velocity field and highlight significant differences between the two cases. In particular, a higher updraft (red areas) is observed close to the collector orifice when no turbulence is included in the free-stream. On the other hand, higher downdrafts (blue areas) are shown in case of turbulent airflow. This result represents a first confirmation of an expectedly higher collection efficiency of precipitation particles when the simplification of laminar airflow is removed. The next step of this investigation is to perform a Lagrangian particle tracking of the hydrometeors in order to quantify the amount of precipitation collected in case of turbulence and to compare the simulation results with field observations.

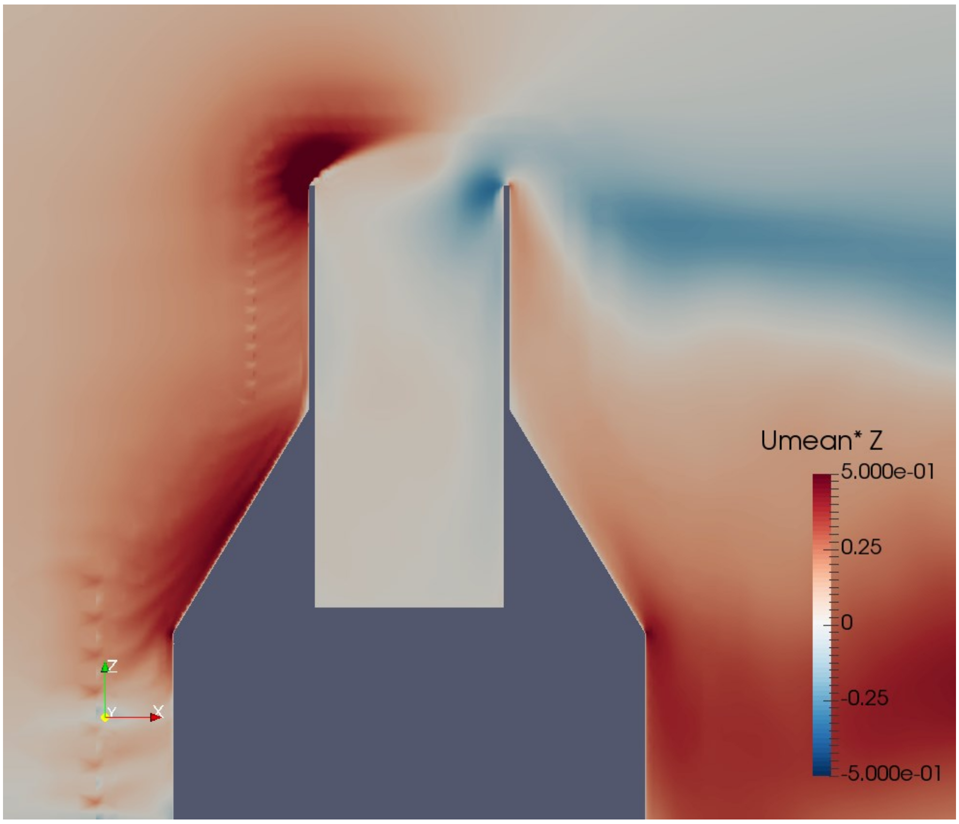

Fig. 7: *Mean vertical component of the air velocity near the gauge collector in absence of the airflow turbulence (LES simulation results).*

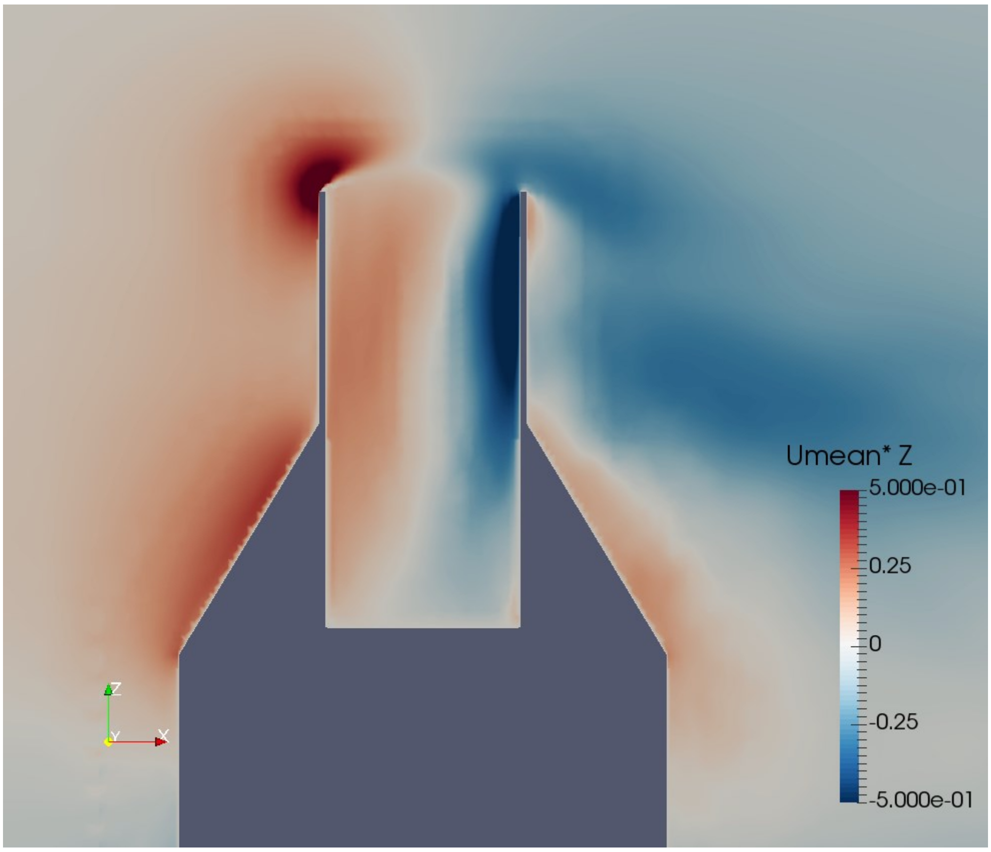

Fig. 8: *Mean vertical component of the air velocity near the gauge collector with airflow turbulence (LES simulation results).*

List of publications/reports from the project with complete references

Since the simulations results are in a post-processing stage, no journal publication has been submitted yet during the previous months. The results of the simulations will be exploited to produce at least one article to be submitted to international scientific journals following the post-processing (e.g. EGU Atmospheric Measurement Techniques, Journal of Hydrology. Atmospheric Research, etc.).

Moreover, a more in-depth post-processing analysis will be presented at international scientific conferences such as the 2017 edition of the EGU General Assembly.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The plan for the continuation of this project is summarized in the following steps:

- One-way coupling of the LES time-dependent airflow results with a Lagrangian particle tracking method to predict liquid and solid precipitation trajectories near to the gauge.
- Post-processing of the LES time-dependent results for data analysis, comparison with field observations and graphical representations.
- Stochastic generation of coherent time dependent turbulent structures at the inlet boundary for future CFD analysis

The previous tasks will be performed during the current year (2016) basing on the aerodynamic fields produced by the *spitlanz* special project. Future projects will aim at extending the methodology to simulate a wider range of mean wind speeds between 1 and 20 m/s and to consider different gauge shapes (e.g. disdrometers).