EFFECTS OF MESH RESOLUTION ON THE SIMULATION OF SEVERE THUNDERSTORM: THE NEED OF PARALLEL COMPUTING AND DISTRIBUTED TECHNIQUES

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***Abstract*— In the design of civil structures, it is necessary to consider the effect of the dynamic loads caused by changes in meteorological conditions such as wind speeds or ice deposits. In Argentina, the Standard of the Argentine Electrotechnical Association (AEA, 2006) is used to calculate structures of electrical transmission networks. This Standard specifies the value that must be assigned to the load by effect of the wind. This value is obtained from the meteorological records measured at conventional meteorological stations such as those of the National Meteorological Service. Nevertheless, to fit this parameter, it is also necessary to carry out local studies with updated information, considering the roughness and, in certain cases, the relief of the ground. Computational mechanics addresses this problem and is currently being used to estimate the values of maximum winds by simulations of severe meteorological events. However, it is also necessary to evaluate the results of this tool to know its accuracy in relation to the parameters of the numerical model. This work shows the use of the Large-eddy Simulation considering two options in the choice of element size used for a geographical grid domain in the thunderstorm occurred in Aranguren, Argentina, in 1998. In the first option, a processor is used to compute this event through a 406-meter grid-spacing in horizontal direction and in the second option a four-processor parallel method is used to obtain a more refined 200-meter grid-spacing. The last option allows simulating severe events such as down-burst or vortex occurrence with more details.**

***Keywords*— Severe thunderstorm, parallel computing, Large-eddy Simulation**.

I. INTRODUCTION

The Standard of the Argentine Electrotechnical Association (AEA, 2006) foresees the possibility of using the probabilistic method to calculate the wind loads in the electrical network of medium and high voltage. This value is obtained from the historical series of meteorological records. Regrettably, in Argentina, several stations of the National Meteorological Service have been deactivated in the last years and the wind data are thus more and more dispersed. Due to low spatial density of meteorological records, it is difficult to analyze the wind data directly. In fact, the probabilistic method needs wind measurements during a long period of time. The reliability of the design is very sensitive to the accuracy of the data provided for their calculation and the parameters used, although the base formulae that allow obtaining those wind loads are well-known (ASCE, 1991). The relation between these phenomena and the effects induced on electrical transmission energy lines has been the concern of numerous studies that aimed to contribute elements that allow less hesitation in their design and construction (Ross *et al.*, 2000; Letchford and Hawes, 2000; Letscher *et al.*, 2002; Lilien *et al.*, 2004; Bjerkan *et al.*, 2004; INTI, 1984; Groupe d'Action 22.11.04, 2001; Working Group, 2010). These works have emphasized the importance of detailed studies in spatial and temporal scale of severe thunderstorm phenomena to obtain more precision in the parameters estimated when designing the electrical transmission network. The studies agree on the importance of obtaining a three-dimensional description of the wind turbulence to obtain the details of these events. In line with this, during the last years, the Large-eddy Simulation (LES) tools have been developed to describe large-scale turbulence. These tools allow obtaining results of large-scale dynamics in the atmospheric boundary layer (Mason, 1989; Schmidt and Schumann, 1989; Esmaili and Piomelli, 1993; Xue *et al.*, 2000). Nevertheless, it is necessary to evaluate the results offered by these tools to know their accuracy in relation to the parameters of numerical model. In this sense, Bryan *et al.* (2003) have suggested that grid spacing in horizontal direction in the order of 100 meters is required to simulate specific details of convective phenomena such as cloud cumulus formation, precipitation distribution and amount, change in phase speed, cloud depth, mesoscale flow patterns and stability structure. Here we used the LES tools considering two options in the choice of the element size of the simulation grid domain. This case of study relates to an event of a thunderstorm occurred in an extensive region of Argentina on January 27, 1998, which caused the collapse of the 132 KV electrical transmission network in the outskirts of Aranguren, Entre Ríos, Argentina. The ARPS (Advanced Regional Prediction System) code developed by the University of Oklahoma and the CAPS (Center of Analysis and Prediction of Storm, USA) was used in its parallel version to reduce the element size used in the grid domain and the results were compared with those obtained in a previous work for the same case of simulation using the sequential version of ARPS.

II. METHODS

The code used for LES was the ARPS (version 5.2.12), a mesoscale model of the non-hydrostatic and fully compressible type, developed by the CAPS. The model numerically integrates the time-dependent equations considering initially the data obtained from an external sounding. The prognostic variables of the model are Cartesian wind components u, v, w and scalars: potential temperature θ, pressure p, air density ρ, mixing ratio of water vapor q_v, cloud water q_c and ice q_i, rainwater q_r, snow q_s and hail q_h. Initially, the states of these variables are included according to *Reynold decomposition* (1) in a base-state $\bar{u}$ and a perturbation u'

$$\begin{aligned}
u(x, y, z, t) &= \bar{u}(z) + u'(x, y, z, t),\\
v(x, y, z, t) &= \bar{v}(z) + v'(x, y, z, t),\\
w(x, y, z, t) &= w'(x, y, z, t),\\
\theta(x, y, z, t) &= \bar{\theta}(z) + \theta'(x, y, z, t),\\
p(x, y, z, t) &= \bar{p}(z) + p'(x, y, z, t),\\
\rho(x, y, z, t) &= \bar{\rho}(z) + \rho'(x, y, z, t),\\
q_v(x, y, z, t) &= \bar{q}_v(z) + q_v'(x, y, z, t),\\
q_c(x, y, z, t) &= q_c'(x, y, z, t),\\
q_i(x, y, z, t) &= q_i'(x, y, z, t),\\
q_r(x, y, z, t) &= q_r'(x, y, z, t),\\
q_s(x, y, z, t) &= q_s'(x, y, z, t),\\
q_h(x, y, z, t) &= q_h'(x, y, z, t),
\end{aligned} \tag{1}$$

The base state of air density is assumed only to satisfy the hydrostatic relation. In this decomposition, the base state is not considered time dependent, so the perturbation is integrated numerically in every time step for the mass balance (2), momentum conservation equation of velocity flow (3) and the scalars momentum conservation ψ (4). Then, these equations are filtered to obtain the large-scales $u_i^{\oplus} = \int u_i G(\Delta x_i) dx_i$, where $G(\Delta x_i)$ is the convolution spatial filter $\int G(\Delta x_i) dx_i = 1$ and Δx_i is the size of grid elements. The variables with tilde indicate that they have been weighted by the density state base $\tilde{u}_i^{\oplus} = \bar{\rho}(z).u_i^{\oplus}$. The pressure equation is obtained by taking the material derivative of the state equation for moist air and replacing the time derivative of density by velocity divergence using the continuity equation. The correlation terms of the scales not solved by LES $(\tilde{u}_i^{\Theta} u_i^{\Theta})^{\oplus}$ are modeled using Smagorinsky formulation (Smagorinsky, 1963; Lilly, 1992) with a dynamic scheme (Germano *et al.*, 1991). Changes in the ARPS code to introduce this technique has been previously made (Aguirre, 2005; and Aguirre *et al.,* 2006).

$$\frac{\partial\left(\tilde{u}_i^{\oplus}\right)}{\partial x_i} = 0. \tag{2}$$

$$\frac{\partial \tilde{u}_i^{\oplus}}{\partial t} + \frac{\partial\left(\tilde{u}_i^{\oplus} u_j^{\oplus}\right)}{\partial x_j} = \bar{\rho} g_i B^{\oplus} - \left(\frac{\partial p'}{\partial x_i}\right)^{\oplus} - \frac{\partial\left(\tilde{u}_i^{\Theta} u_j^{\Theta}\right)^{\oplus}}{\partial x_j} + 2\frac{\partial \tilde{S}_{ij}^{a\oplus}}{\partial x_j}. \tag{3}$$

$$\frac{\partial \tilde{\psi}^{\oplus}}{\partial t} + \frac{\partial\left(\tilde{u}_j^{\oplus} \psi^{\oplus}\right)}{\partial x_j} = S_{\psi} - \frac{\partial\left(\tilde{u}_j^{\Theta} \psi^{\Theta}\right)^{\oplus}}{\partial x_j}. \tag{4}$$

In the previous equations, B is a buoyancy force, S_{ij}^{a} is the anisotropic deformation tensor and S_{ψ} are the sink and sources of the scalars quantities ψ. This model has been designed specifically to pursue and describe thunderstorms. Sub-models of heat flow and water steam, cloud formation and precipitation are included. Ground relief, vegetation types, soil types and initial conditions of the atmospheric state are taken into account. The ARPS model uses a special case of the fully three-dimensional curvilinear coordinate system where the size of horizontal grids is constant but the vertical coordinate follows the terrain elevation and a stretching in size is applied to obtain more accuracy near the ground. The results of the dynamics of the simulated flow have been previously compared (Aguirre *et al.*, 2007) with those obtained by measurements in a wind tunnel for a case of rough soil in the presence of one slow hill (Gong and Ibbetson, 1989). In another work, a severe thunderstorm which had occurred in Aranguren, Entre Ríos, Argentina, on February 27, 1998, was simulated using a sequential version of ARPS (4.5.2) with a 143 x 113 grid element mesh in horizontal direction spread regularly over 406 meters and 36 elements in vertical direction (Aguirre *et al.*, 2009). The details related to the numerical scheme can be read in Xue *et al.* (1995, 2000, 2001).

A. Microphysics model

The parameterization of the microphysical processes of water simulates the condensation, evaporation, cloud formation and precipitation. This submodel of parameterization is called *warm-rain microphysics* and is based on the descriptions of Klemp and Wilhelmson (1978) and Soong and Oruga (1973). There are also other more sophisticated submodels that include the simulation of the formation and precipitation of water in the solid state as well as the formation of clouds (Lin *et al.*, 1983; Ćurić and Janc, 1993; Ćurić *et al.*, 1999, 2003, 2009; Gharaylou *et al.*, 2009) which will be object of future works. The authors of the *warm-rain microphysics* parameterization model consider three water categories: water vapor (q_v), cloud water (q_c) and rainwater (q_r), where the latter two are characterized by its size. At the beginning of the process, cloud water droplets are formed when the air comes to the saturation state of the water mixing ratio and condensation occurs. Then, if the water mixing ratio in the saturated air to the interior of the cloud exceeds a critical threshold, raindrops are formed that later begin to fall and increase in size for coalescence of the small droplets of the cloud that they find in their way. If after crossing the base of the cloud they meet air below the saturation point, then the process of evaporation breaks loose, gradually diminishing the size of the raindrops. The time rate of evaporation, condensation and change of category processes will depend on certain parameters and on the water mixing ratio in the air. As all these processes involve transference of energy in heat and latent vapor, it is necessary to fit the potential temperature of the air. The theoretical formulation will not be described here because it is not the aim of the present work. For more details of the microphysical processes in the ARPS code, see Xue *et al.* (2000).

B. Parallel version of the Simulation

Here we implemented the parallel version of the ARPS (5.2.12) code to achieve a spatial resolution reduced for horizontal directions with regard to that used in Aguirre *et al*. (2009) with the sequential version of ARPS (4.5.2) for the same physical dimensions of the domain calculation. No domain decomposition was carried out in the vertical direction due to the implicit scheme resolution of the dynamic flow and microphysics parameterization model because their algorithms have vertical dependencies. To obtain a better horizontal resolution of the grid, a domain decomposition of the full computational grid can be used to obtain sub-domains for each processor of the cluster. If this parallel version is to be used, inter-processor communications are required at the boundary of the sub-domains. In this work, we used the Message Passing Interface (MPI) standard strategy for inter-domains communication. For more details on this technique in the ARPS code, see Xue *et al.* (1995, 2008).

III. CASE OF STUDY

The severe thunderstorm occurred on January 27, 1998, in Aranguren, Entre Ríos, Argentina, caused large mechanical ravages, such as destruction of roofs of sheds and housings, and knocked down some telephone poles and several concrete pylons which support high voltage electrical transmission networks. These pylons were 22 meters tall, had a foundation depth of 2.20 meters and a base diameter of 0.5 meters. Although this thunderstorm had its largest intensity in this area, it also caused ravages in other cities of the central area of the country.

The information compiled by the stations of the National Meteorological Service indicates the presence of a very humid and unstable air mass that unleashed numerous thunderstorms when a colder air mass coming from the south-west displaced it. This phenomenon was recorded by some stations near Aranguren but not in Aranguren itself for there is no meteorological station in this town. Figure 1 shows the geographical location of Aranguren and other nearby stations of the National Meteorological Service in the cities of Santa Fe, Paraná and Rosario. The rain thunderstorm reached Rosario on January 27 and then Paraná between January 27 and 28. In this last city, precipitation reached 123 mm. The change in the atmospheric pressure along with the decrease in temperature denotes the rapid irruption of air mass relatively colder than that present in those days. These conditions caused maximum winds (averaged in 10 minutes) of 35.2 km/h in Rosario and of 33.5 km/h in Paraná. Regrettably, the maximum blasts (maximum value of the average speed considering 3 seconds) were not recorded. These blasts were surely higher than the indications of ravages which occurred in several spots of the area. One of them, Aranguren, was the one that suffered the most severe damage.

As mentioned previously, this case of study relates to a thunderstorm occurred near Aranguren, and emphasizes on the maximum values of wind speeds that caused the fall of 132 KV electrical transmission networks pylons (Fig. 2). These concrete pylons were designed following the technical specification of Water and Energy Commission of Entre Ríos Province of 1960, based on the VDE 0210 norm, for a wind speed of 130 km/h.

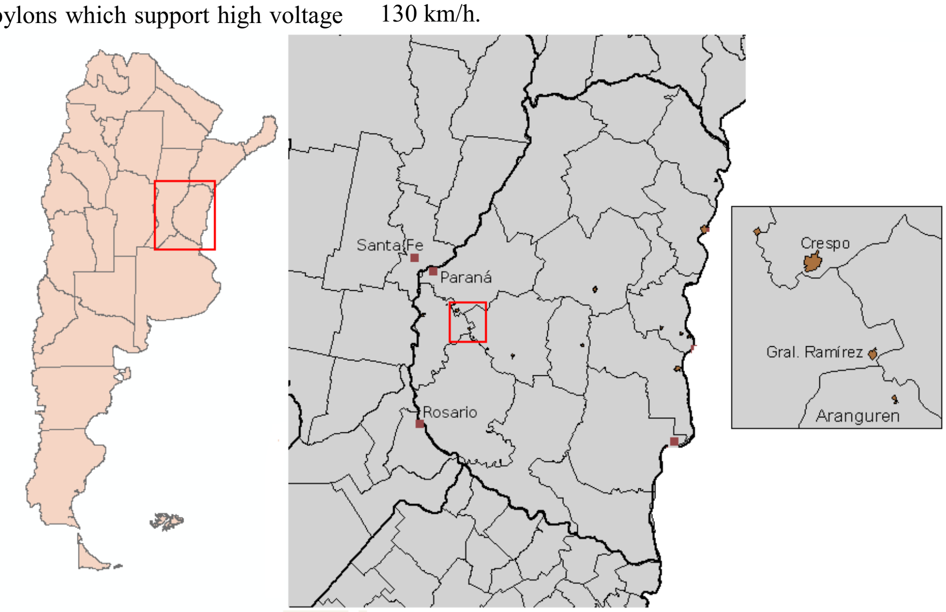

Figure 1: Aranguren town in Entre Ríos Province, Argentina.

Figure 2: Damages of the pylons that support of electrical transmission network. (Courtesy of ENERSA S. A.)

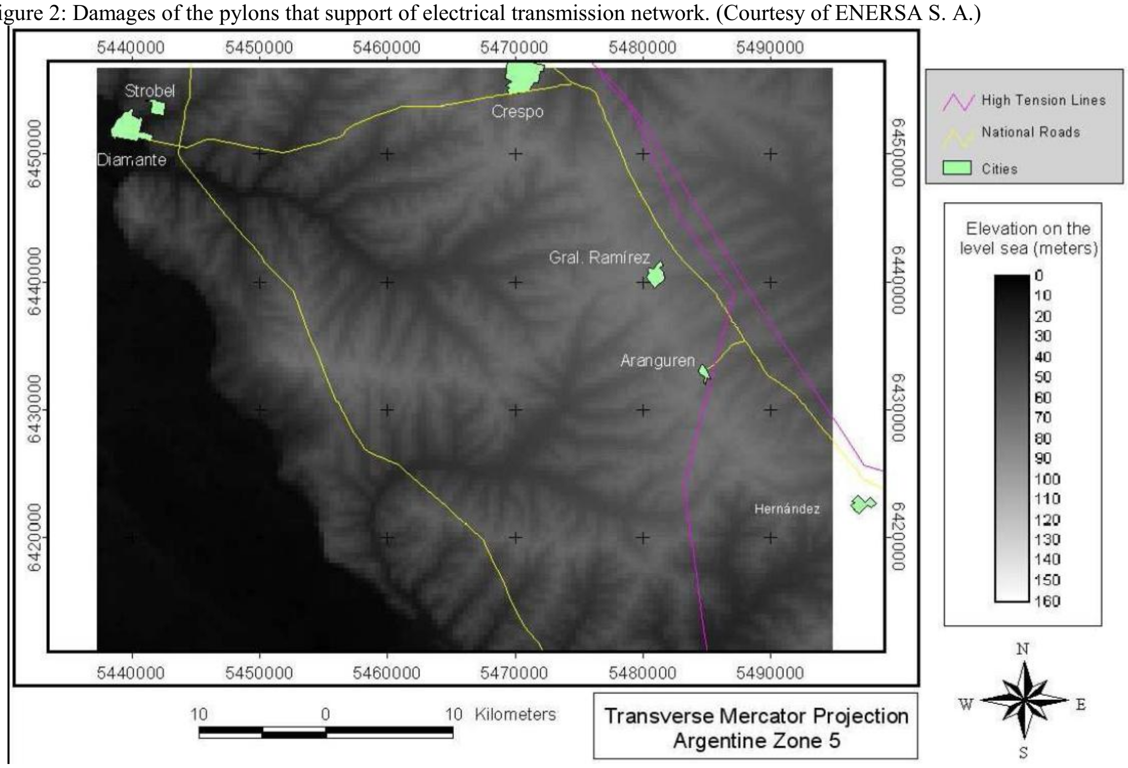

Figure 3: Domain of calculation: Digital Elevation Model and electrical transmission network of high voltage.

IV. COMPUTATIONAL DETAILS

In the west-east direction, the physical domain of calculation extends from the east margin of Paraná river to Hernández town, whereas in the north-south direction it extends from Crespo town to 12 km south of Hernández town, demarcating a rectangular area of 60 km in west-east direction and 46 km in north-south direction. Here, we used a digital model of elevation obtained from Radar images published by the U.S. Geological Survey (2002) with a spatial resolution of 80 meters, processed by Brizuela (2004). In previous works (Aguirre *et al.*, 2009) carried out the simulation with the sequential version of the code ARPS (4.5.2) using a spatial horizontal 406-meter cell resolution grid because the computational time does not allow a better refinement of the mesh. In this work, the parallel version of ARPS (5.2.12) was used to achieve a better spatial horizontal

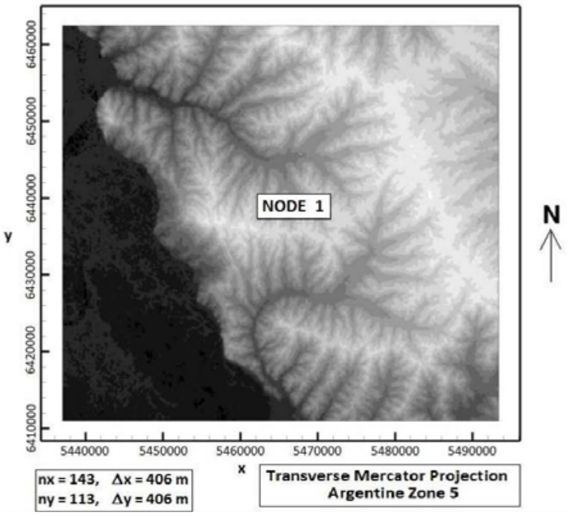

Figure 4: Domain of calculation scheme used in Aguirre *et al*. (2009).

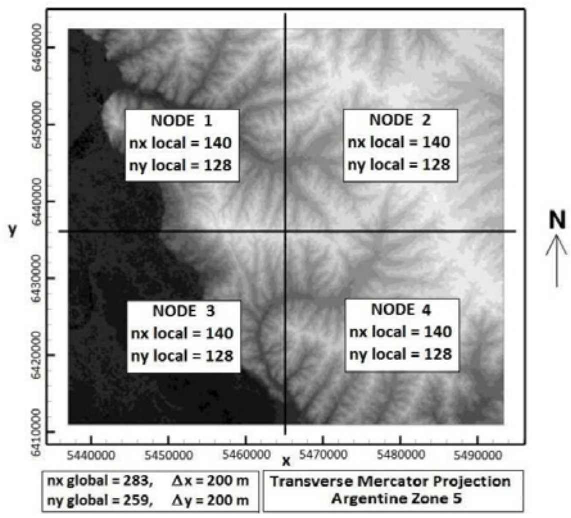

Figure 5: Domain of calculation scheme used in this work.

resolution, taking it to 200 meters. The coordinate system used was Transverse Mercator Argentina Zone 5, whose ordinate is 60 degrees west meridian. This system is based on the ellipsoid WGS 1980 and updated with the network measurements POSGAR 98. Figure 3 shows the extension of the physical domain of the simulation carried out in this work and the digital model of elevation, some important towns, the routes and the trace of the electrical transmission network at a high voltage of 132 KV. Figure 4 shows the scheme of the horizontal domain used in Aguirre *et al.* (2009) with one processor to calculate the full computational domain of 143 x 113 x 36 grid points for a 406-meter cell resolution grid in horizontal direction (case A). Figure 5 presents the scheme used in this work. In this case (case B) the simulation was run in parallel with a distributed memory machine using the MPI technique with four processors, each resolving ¼ of the computational domain. The size of the sub-domains for each processor is 140 x 128 x 36 grid points for a 200-meter cell resolution grid in horizontal direction. The last simulation (case C) was run with a parallel version of ARPS using four processors with 406 meters to compare the results obtained in Aguirre *et al.* (2009) (case A). The initial conditions of the simulation were obtained from information of a sounding carried out on January 26, 1998, at the meteorological station of Córdoba city, Argentina. Figure 6 shows the SkewT-LogP diagram. The Level of Free Convection (LFC) happens approximately at 750 HPa. The moisture in low layers is raised up to this level and between 500 HPa and 300 HPa. The Convective Available Potential Energy (CAPE) extends from the LFC to the Equilibrium Level (EL) at 180 HPa. This area of the diagram lies between the broken line of the right side and the curve of potential temperature of the left side. It is large, which indicates that the conditions of instability are favorable for the formation of severe thunderstorms. The boundary conditions are of the forced type for the horizontal component of the wind field and the potential temperature on the west side of the domain follows the technique proposed by Lund and Squires (1998) whereas on the other boundary radiation conditions (Klemp and Wilhelmson, 1978) were used. The total physical time of simulation was 3960 seconds using a time step of 0.1 second to solve Eqs. (2), (3) and (4) and of 0.05 seconds to solve the pressure equation.

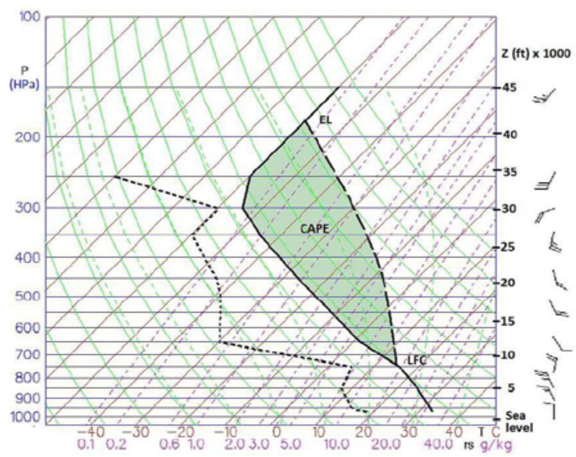

Figure 6: Skew T-Log P diagram of sounding balloon obtained on 26 January 1998 in Córdoba City.

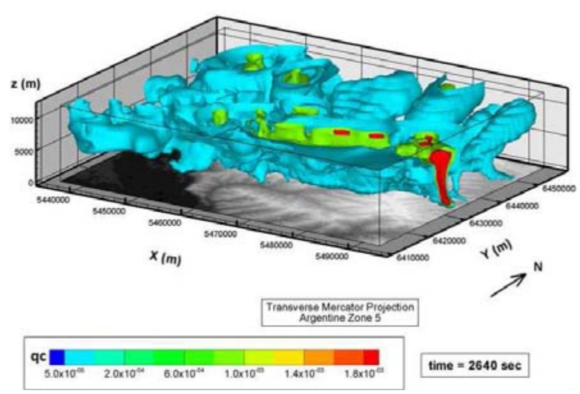

Figure 7: Three-dimensional view point of clouds at 2460 seconds of physical time. q_c: Mixing rate of cloud water.

V. RESULTS

Figure 7 shows a three-dimensional sight of the cloudy formations at 2460 seconds from the beginning of the entry of cold air mass into the area. Three iso-surfaces of water concentration are seen in the liquid state. It is observed that the frontal area advances from the south and there are also cloudy convective formations causing strong winds in front of them.

Figure 8 presents a viewpoint from east of the simulation domain at the same time. It can be observed that some cloudy formations extend towards the ground in the shape of maelstrom where the ascending currents are more intense, which simulate the probable occurrence of a vortex.

Figure 9 and 10 show a viewpoint from the south of a sector where a cumulonimbus is observed. Figure 9 shows the simulated air flow in an X-Z plane and the water concentration in liquid state. Figure 10 shows a viewpoint from the south of the same sector. The strong ascending and descending currents of air are observed within the cloud and the strong wind speeds that take place close to the ground.

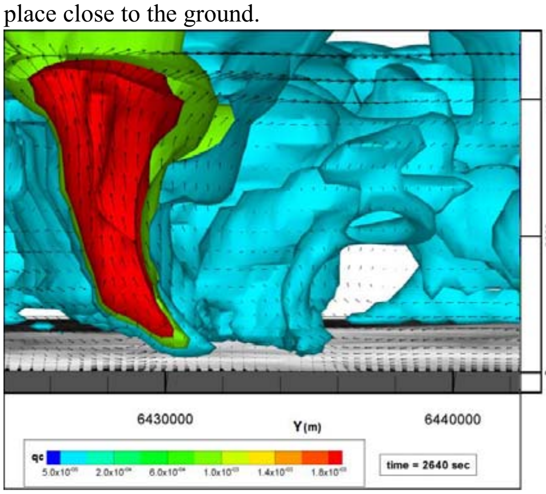

Figure 8: Viewpoint from east (Y-Z plane section) of the simulation domain at 2460 seconds of physical time. q_c: Mixing rate of cloud water.

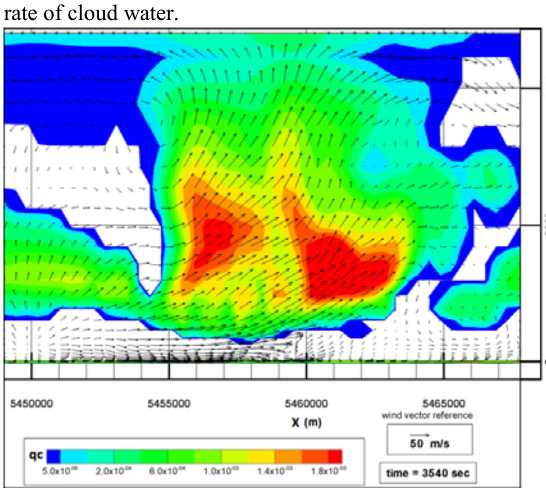

Figure 9: Viewpoint from the south of the cumulonimbus: X-plane section.

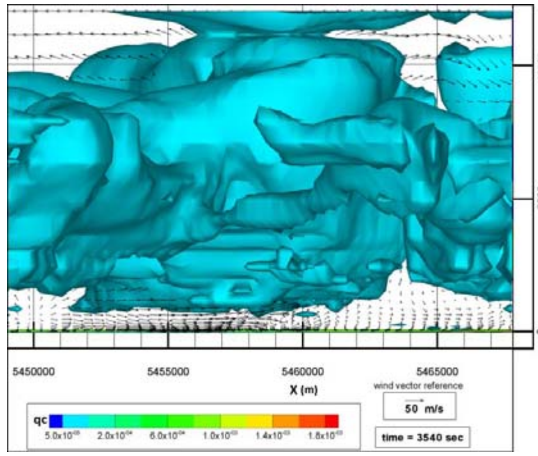

Figure 10: Viewpoint from the south of the cumulonimbus: Cloud.

Figure 11 and Fig. 12 show a top viewpoint of the temporary sequence of the trace of a probable vortex and the simulated values of speed and wind direction at 22 meters of elevation (top end of the suspension pylons of electrical transmission network). The vectors indicate only the wind direction; the wind speed is shown in a color scale. The sequence goes from 3240 seconds to 3780 seconds of physical time from the beginning of the simulation. The evolution of the situation is shown every 60 seconds.

Figure 13 allows observing the temporary evolution of the wind speed simulation and its direction at 22 meters over the ground in the place where the pylons of electrical transmission network of 132 KV broke and fell. The left side shows the results using the coarse grid with the sequential version code (Aguirre *et al.*, 2009) and the parallel version code (present work). The right side shows the results obtained using the parallel version code with a refined grid.

Figure 14 shows the temporary evolution of the maximum wind speed simulation at 22 meters over the ground following the trajectory of the vortex shown in Fig. 11 and Fig. 12.

Table 1 presents the wall-clock time for 1 hour of physical time simulation using the sequential version (ARPS 4.5.2) with 406 meters in a spatial horizontal resolution grid (case A), the ARPS 5.2.12 in parallel version with four nodes and 200 meters in a spatial horizontal resolution grid (case B), and the ARPS 5.2.12 parallel version with four nodes and 406 meters in a spatial horizontal resolution grid (case C).

VI. DISCUSSION

The comparison between the results of the simulation obtained in Aguirre *et al.* (2009) using the sequential version of ARPS (4.5.2) with coarse grid and the results of the present work using the parallel version of ARPS (5.2.12) with four processors of the cluster with refined grid shows the following differences:

- The cloudy convective formations of the cold front take place earlier in the simulation of Aguirre *et al.* (2009) than in that of the present work. This evidences that the cloud simulation with the *warm-rai*n *microphysic*s parameterization model is not independent of the spatial horizontal resolution grid. This dependence is not due to the microphysics model, but due to the numerical scheme used (the finite differences).

- Figures 11 and 12 show the simulation of a well-defined vortex and its sinuous trajectory, although it is not found in the simulation of Aguirre *et a*l. (2009). This shows that is not possible to obtain a detail of the micro-systems within the convective clouds with a relatively gross spatial horizontal resolution grid.

Table 1: Computational time for 1 hour of physical time simulation with the ARPS 4.5.2 sequential version and ARPS 5.2.12 parallel version.

CC	Code	N	SR	PHT	WCT
(A)	4.5.2	1	406 m	1 hs	140 hs 35´
(B)	5.2.12	4	200 m	1 hs	144 hs 54´
(C)	5.2.12	4	406 m	1 hs	27 hs 49´

CC: Case. Code: Version of ARPS code.
N: Number of processors. SR: Spatial horizontal resolution. PHT: Physical time. WCT: Wall-Clock Time.

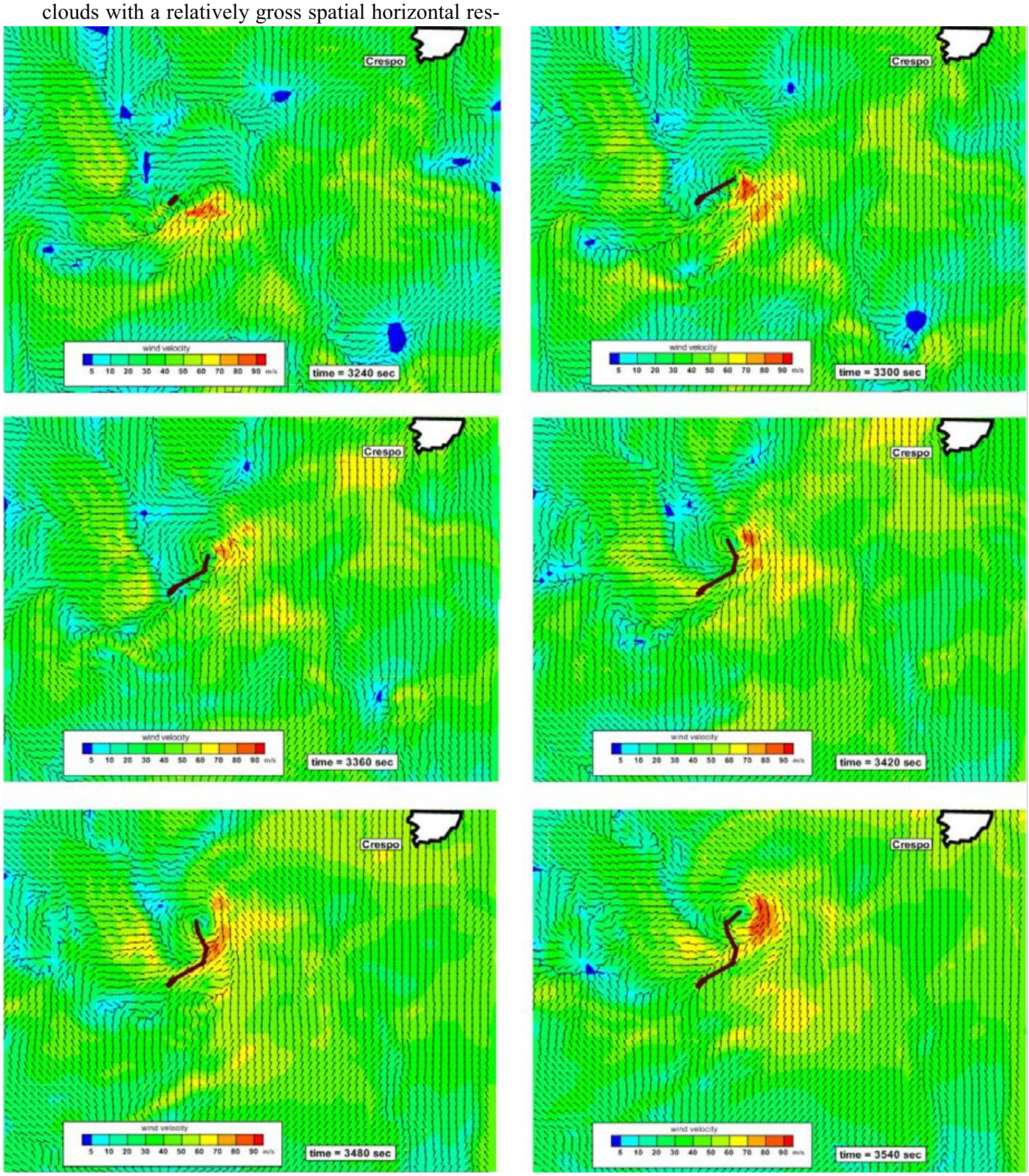

Figure 11: Trajectory of a vortex from 3240 to 3540 seconds obtained with refined grid (Case B). →: Wind direction. Brown line: trajectory.

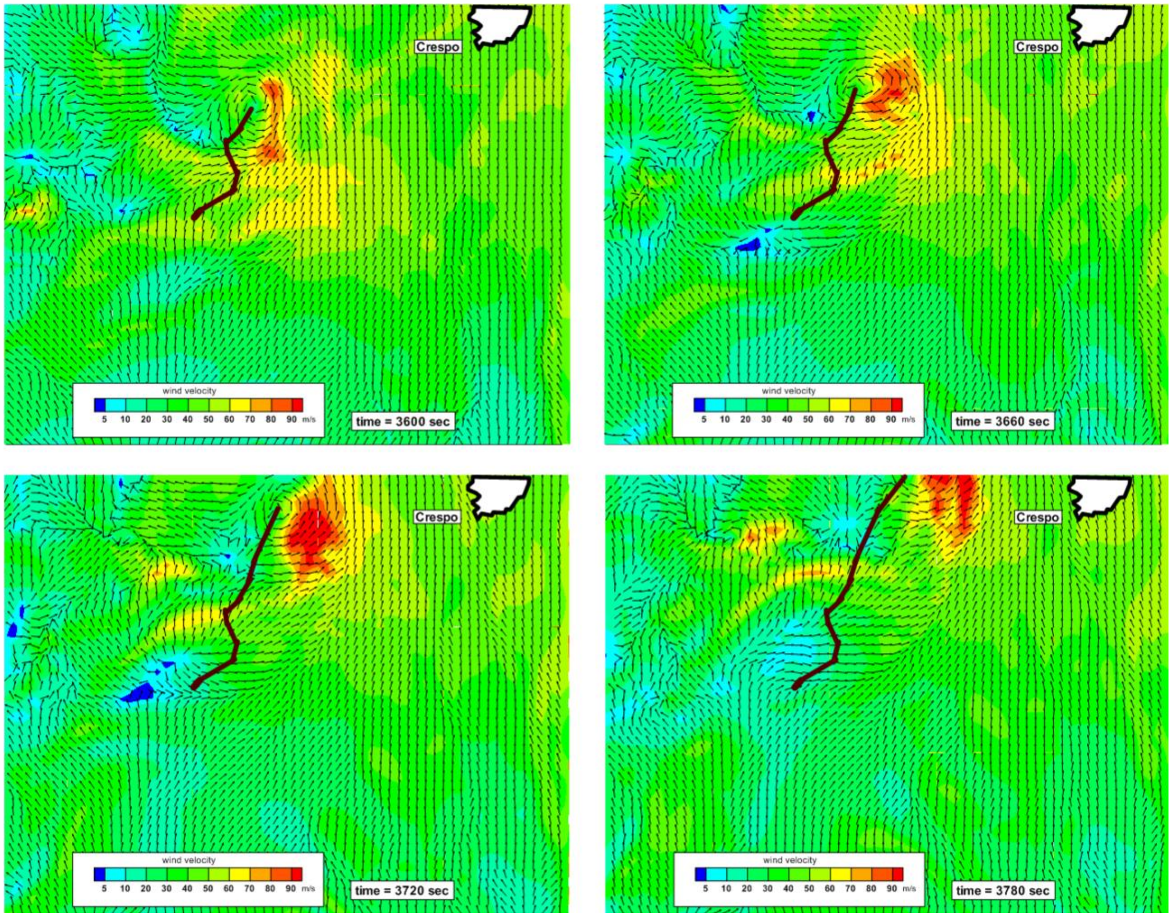

Figure 12: Trajectory of a vortex from 3600 to 3780 seconds obtained with refined grid (Case B). →: Wind direction. Brown line: trajectory.

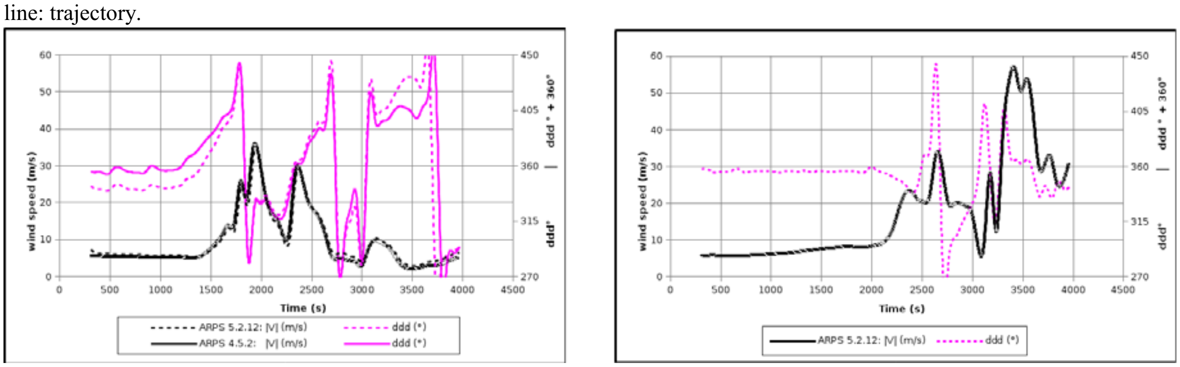

Figure 13: Temporary evolution of the wind speed simulation (|V| m/s) and direction (*ddd*°) at 22 meters over the ground in the place where the electrical transmission network pylons broke and fell.
Left: Results of the sequential version code ARPS 4.5.2 obtained in Aguirre *et al.* (2009) -case A - and parallel version code ARPS 5.2.12 (present work) -case C - both with coarse grid (406 meters of spatial horizontal resolution grid).
Right: Results of the parallel version code ARPS 5.2.12 (present work) -case B - with a refined grid (200 meters of spatial horizontal resolution grid).

- Figure 13 shows the maximum wind speed at 22 meters over the ground (top end of the suspension pylons for electrical transmission network) in the place of the collapse, which is larger in the present work than in Aguirre *et al.* (2009). Also, the highest value of wind speed at the same elevation obtained in the domain of calculation in Aguirre *et al*. (2009) is 52 m/s whereas in the present work it is 110 m/s (Fig. 14). This shows the important influence of the spatial horizontal resolution grid proposed for the simulation.

VII. CONCLUSIONS

The code of Large-eddy Simulation ARPS is a tool that allows obtaining a three-dimensional description of the events of severe thunderstorms, their characteristics, and their temporal and spatial evolution.

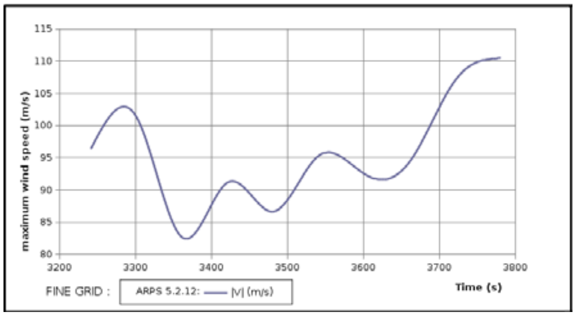

Figure 14: Temporary evolution of the maximum wind speed simulation (|V| m/s) at 22 meters over the ground following the trajectory of the vortex shown in Figs. 11 and 12.

The accuracy of the results obtained is narrowly tied to the spatial horizontal resolution grid of the calculation domain.

The micro-systems of low pressure that are formed into convective clouds and that are the cause of ravages because of their high wind speed cannot be simulated by this code if the horizontal spatial resolution grid is too low to simulate it. So, it is necessary to refine the calculation grid to capture the appearance and space-time evolution of a vortex. If the parallel version of ARPS code is used, this can be done without sacrificing the wall-clock time.

Compared to the sequential calculation, the wall-clock time decreases when four nodes of the cluster for the same grid spacing in horizontal direction are used and it is approximately equal when the grid spacing is decreased to half.

The code in its version of parallel calculation ARPS (5.2.12) using a 200-meter cell resolution grid in horizontal direction allowed simulating the evolution in space and time of a vortex which was 400 meters in diameter. This event went unnoticed in the simulations carried out by Aguirre *et al.* (2009).

The values of maximum wind speed obtained as a result of the simulation with the refined calculation grid were 110 m/s, whereas in the case of the simulation using a cell which was double in size, the maximum value of wind speed simulated was 52 m/s.

The *warm-rain microphysics* parameterization also depends on the spatial horizontal resolution grid, therefore, on the number of resolved turbulent scales.

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