PROJECT TITLE: Advanced Numerical Methods for Environmental Management

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Reference: CGL2011-29396-C03-00

ULPGC-Subproject Title: Advances in Wind Field and Solar Radiation Simulation

Reference: CGL2011-29396-C03-01

Project Coordinator : Prof. Rafael Montenegro Armas

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1 Aim of the project

Nowadays numerical modelling has become an essential tool for the analysis and prediction of a large number of physical phenomena. The numerical modelling includes the mathematical modelling of the phenomenon and the numerical resolution of the involved mathematical problem. This Project is focused on four environmental phenomena: (1) wind field simulation, (2) air pollution numerical modelling and forecasting, (3) forest fire simulation and (4) solar radiation simulation. Although they are four different problems, there exist many points in common among them. All of them are defined in similar types of domains and thus the same discretization techniques can be used. The wind modelling results critically affect the air pollution and forest fire modelling. Thus the former problem is essential for carrying out the other simulations. In addition, wind modelling has its own applications (wind maps). Air pollution and forest fires are related to unsteady propagation problems which may be mathematically described by a convection-diffusion-reaction equation and thus solved by using similar numerical techniques. The solar radiation modelling is also an environmental problem of which the nature is mostly geometrical. Our experience on adaptive discretization techniques has encouraged us to include this topic in the proposal, as a response to the interest of some companies working on solar radiation maps. Finally, all four phenomena have clear technical applications. Among them, we emphasize: the construction of wind maps, the study and control of pollutant emissions, the planning for anti-fire measures and the construction of solar radiation maps. For this reason, we propose a joint treatment of the four problems in the context of this coordinated project.

Currently, realistic simulations are associated to the availability of meteorological observation data and to the access to the geographic information systems. The meteorological observations are periodically available through different networks and they are the input data for mesoscale models. Among them, perhaps MM5 (Fifth Generation of Mesoscale Model, http://www.mmm.ucar.edu/mm5/, Pennsylvania State University, National Center for Atmospheric Research, USA) is actually the most widespread prognostic model. This is a well-known and free model supported by NCAR (National Center for Atmospheric Research) to which many research groups have added their own software, both in the model core and in data pre-processing and post-processing. Obviously, other similar models as WRF, HIRLAM or HARMONIE are used by the meteorological community. In the field of multiscale air quality models, the CMAQ (Community Multiscale Air Quality Model, NOAA-EPA, USA) has been widely used and it is a reference of this kind of models. The idea is that a mesoscale model (MM5, HIRLAM, WRF, CMAQ, MOCAGE,...) provides the input data for our adaptive high resolution finite element models. So, a main objective of this project is to refine the results of a mesoscale model (with a maximum resolution about 1 Km) in a local scale (about a few meters). This idea is summarized in Figure 1. In addition, data assimilation is a technique that can improve the reliability of the simulation. If during the spread of pollutants or the propagation of a fire we have experimental data, the integration of these data with the results provided by the models can correct and improve the predictions.

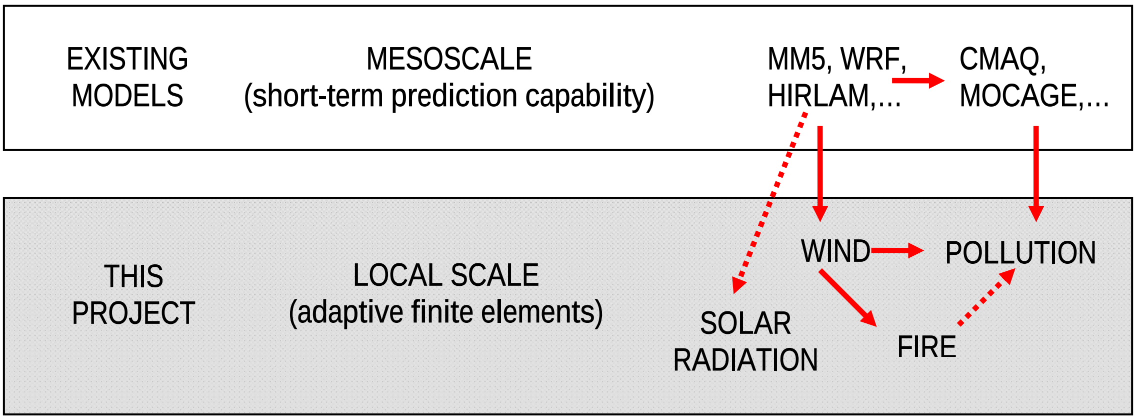

Figure 1: The goal of this project is to develop advanced numerical models at the local scale and to integrate them with existing models at the mesoscale. Solid arrows indicate clear connections while dashed arrows are connections of a more exploratory nature.

1.2 Background and current state

The three groups that present this proposal (Universitat Politècnica de Catalunya, UPC, Universidad de Salamanca, USA, and Universidad de Las Palmas de Gran Canaria, ULPGC) have finished together three previous coordinated projects sponsored by Spanish Government and FEDER: “Modelización Numérica de Problemas Medioambientales de Convección-Difusión-Reacción” (REN2001-0925-C03; 2002-2004), “Modelización y Simulación Numérica de Procesos Medioambientales” (CGL2004-06171-C03; 2005-2007) and “Modelos Numéricos Predictivos para Gestión Medioambiental” (CGL2007-65680-C03; 2007-2008). Besides, these three groups are currently carrying out the project “Modelos Numéricos Predictores para Gestión Medioambiental” (CGL2008-06003-C03; 2009-2011) that will be finalized at the end of 2011. The Agencia Estatal de Meteorología, AEMET, the Instituto Tecnológico de Canarias and Tecnosylva have an active participation in this project as EPOs. Scientific results of these four projects (including researchers, objectives, files of papers, congress communications, thesis, congress organization, books, software, workshops, awards, etc.) can be downloaded from http://www.dca.iusiani.ulpgc.es/proyecto2008-2011, http://www.siani.es/, http://www-lacan.upc.es, http://web.usal.es/~ferragut, etc.

1.2.1 Wind field simulation

A considerable number of scientific works has been published about wind modelling in 3-D along the last thirty years. On the one hand, the ULPGC group has experience in the development and application of this type of models since 1986 (see references [1.1], [1.3], [1.4], [1.5], [1.6] and [1.7]) in the framework of several projects financed by public institutions. On the other hand, the USA group has developed a wind model based on an asymptotic approximation of the Navier-Stokes equations [1.8], [1.9]. The numerical solution of this type of models can be calculated efficiently [1.10] and the quality of the approximation is comparable to the approximation provided by 3D modeling, see [1.1].

In this new project we will introduce a new 3-D mesh generation techniques based on the meccano method [1.2] adapted to complex terrains and urban environment. The mesh adaptation should be done related to terrain height, roughness length, coastlines, chimneys, etc. Our objective will always be minimal user intervention and low computational cost. We will design and develop a framework for the mesh generator and wind simulation. This tool will be common for the three subprojects since their simulations are defined on similar domains and the wind is the main magnitude that governs the transport phenomena. On the other hand, we propose a new approach of the initial wind field. For this purpose, our model must construct the initial wind field by using a suitable interpolation of the mesoscale model results. So, an interface between both models should be implemented and transfer to EPOs. The final goal is to validate our models in several realistic applications for construction of wind maps and forecast in several regions of Spain. These wind maps will be used in air pollutant modelling.

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1.2.2 Air pollutant numerical modelling and forecasting

In the last project, the Finite Element Method with unstructured and topographically adapted meshes has been successfully proposed as an alternative to usual modelling and forecasting of air quality at local scale (with domains of about one hundred km^2 and precisions about meters in areas of interest). Forecasting character of simulations at local scale [2.1] come from coupling with regional meteorological and air quality models (with uniform grids, precision, about 1 or 2 km at most, and linked throughout nested models with global atmospheric dynamics). However, to link meteorological forecasting with local air quality is still an open problem in different aspects, the following are those addressed in this project: Local wind dynamics needs to be improved in order to include vortices when needed (close to sharp topography and built environment, as urban areas) with a real three-dimensional approach; Information to run local model (winds, temperature, inmission levels,…), not integrated in regional forecasting, has to be included when desired, following data assimilation processes as those used in regional forecasting. Advanced numerical strategies has to be develop in order to manage memory and CPU time demands of these new developments in manageable limits.

In the previous project, it has been shown that transport-reaction problem can be solved with meshes with element sizes ranging from meters to kilometres and with one to two million elements. New developments will require precision in more parts of the domain than before, but problem size has to be kept under control in order to be solvable. Due to the will to manage standard non-linear reaction chemical models (which typically involve tens of species) Finite Element meshes are limited in size. This fact represents a handicap from the point of view of transport, which also requires geometrical precision. To overcome this difficulty, we propose to develop specific three-dimensional adaptive schemes for transport.

In the same direction, but with respect to local wind dynamics, vortices will be included throughout considering incompressible Navier-Stokes model, with the aim of better downscaling the dynamics of the regional meteorological models (which are based on the Euler equations). But, in order to keep the number of unknowns under control a DG approach is proposed [2.2], [2.3]. Actually classical Computational Fluid Dynamics simulation, such as the ones performed with Ansys-Fluent, uses finite volume methods. In this case, increase in accuracy can only be obtained by refining the mesh, whereas in a DG formulation as the one we propose, here, we can work with coarse meshes and increase easily the order of the interpolation within each element. Large Eddy Simulation model is planned to be added to take into account the turbulence phenomena of the flow.
On the other hand, data assimilation of local available measures is needed also at the local scale. It will be analyzed, taking advantage of the work in fire simulation (see next section).
New developments will be compared with published experimental data [2.4] and other simulation results [2.5] [2.6]. Moreover, the research team will collaborate with the Lab of the Environmental Center (Chemical Eng. Dept., UPC). They have data of case studies in urban area [2.7] which will be used to validate the proposed approach of this project.

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1.2.3 Forest fire simulation

This research project aims to obtain a new scientific knowledge based on the numerical simulation of forest fires, which contributes to the conservation of our forests, by its protection against forest fires. The simulation of forest fires has a direct application in the work of prevention and extinction.
The main existing models are of different nature (combustion models and propagation models). Models based on the cellular automata theory [3.1]. Geometrical models, where the fire front is computed by the envelope method [3.2]. Empirical models, where the rate of spread of the front is given by an empirical law [3.3]. Finally, physical models derived from general conservation laws of mass, energy and momentum [3.4].
Our research group has developed diverse forest fire physical spread models [3.5], [3.6]. They are simplified models with the aim of simulate a fire spread with computing times significantly lower than the real time, but taking into account the most important mechanisms of fire spread such as the moisture content or the non local radiation [3.7]. In addition, our research group has established a close collaboration with the company Tecnosylva S.L. This company, has developed a tool for the analysis of forest fires spread and a high-resolution cartography service of forest fuels. Recently this relationship has been strengthened, as our research group is an Public Research Partner (OPI) of Tecnosylva as

part of a CENIT project: PROMETEO. Our research group will have access to data from real fires. This project would contribute to the validation, development of the models and efficiency improvements.

The propagation models developed by our research group are based on conservation laws. Mathematically the problem is reduced to solve one or several partial differential equations. To solve this partial differential equations we do an extensive use of the adaptive finite element method (AFEM). [3.8], [3.9], [3.10].

Concerning forest fire simulation the main goal in this project is the integration of experimental data. Data assimilation allows to correct the predictions obtained by the simulations and provides better predictions in the following steps. One of the methodologies used in data assimilation is the variational method, based on control theory, which has been widely used in meteorology and oceanography [3.11], [3.12]. Another alternative, when the uncertainty in the measurements and parameters is high, is common to work with random variables. In this way, certain covariance matrices quantifying the errors produced in the measurements and even in the model. In this sense, some of the methods are the so-called 3D-var and 4D-var [3.13]. These methods require prior or empirical knowledge of the covariance matrices. In the early sixties, Rudolf E. Kalman [3.14] developed what would later become known as Kalman Filter [3.15]. The Kalman filter is a mathematical procedure that eliminates the "noise" and allows obtain the best estimates of a state, combining the prediction provided by a model of the phenomenon and the experimental data.

There are several variants of Kalman Filter that extend its use to non-linear problems: the Extended Kalman Filter (EKF) and the Ensemble Kalman Filter (EnKF). The first proposed the approximation of the corresponding model by a linear model followed by the classical version of the filter [3.16]. The second alternative combines the Kalman filter with a Monte Carlo method: The initial solution is perturbed to work with a sample of states. The variance matrix of the error is replaced by the sampling variance. However, the simulation of a large number of states is required. The efficient implementation of the process requires parallel techniques and the use of large computers.

The EnKF has been widely applied in recent years and has been successfully implemented in the simulation of ocean currents and meteorology [3.17]. This experience suggests that the adaptation of these techniques to the physical models of spreading improve the predictive ability of the models [3.18]. The techniques of data assimilation should allow changing the outcome of the simulations in a way that these are consistent with the measurements, even in the case in which the initial conditions have been taken with a significant error.

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1.2.4 Solar radiation simulation

In this project we propose an adaptive solar radiation model as a new tool for generating solar radiation maps [4.3]. We introduce an improvement to existing models [4.4, 4.5] with mesh adaptation to terrain height, albedo distribution and coastlines [4.1, 4.2]. This adaptive approach will allow us to develop more efficient codes with a reduction in the computational cost for a given accuracy. It should also be interesting the treatment of shadow boundaries in each time step by using virtual adaptive procedures. Solar radiation is first computed for clear-sky conditions, considering the different components of radiation: beam, diffuse and reflected radiation. The real-sky radiation is computed daily starting from the results of clear-sky radiation, in terms of the clear-sky index. Maps for clear-sky index are obtained from a spatial interpolation of observational data available for each day at several points of the zone under consideration. Finally, the solar radiation maps of a month or of a year are calculated from the daily results.

The model can be also applied in solar radiation forecasting. To do so, a forecasting meteorological model is required. The estimation of daily solar radiation provided by such model is used to adjust the clear sky results and obtain the real-sky radiation. In addition, the information of overcast condition provided by the forecasting meteorological model can be used for the real-sky estimation.

The model can be used in atmospheric sciences as well as in other fields like electrical engineering since it allows the user to find the optimal location for the maximum power generation in photovoltaic, or solar thermal power exploitations, [4.6] and to reach an optimal management of electrical networks.

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1.3 Related national and international groups

In Spain there are several research groups in meteorology (fundamental physics, modelling of mesoscale and synoptic scale meteorological phenomena, global change, statistic analysis, etc.). Many of them provide important contributions in the field of numerical simulation in meteorology. The ULPGC group belongs to the international network "Red Ibérica MM5/WRF" (http://redibericamm5.uib.es) which involves 47 scientific groups on applications of MM5 and WRF leaded by "Grupo de Meteorología" of the Universidad de las Islas Baleares. The main contribution of our groups is on numerical methods in Applied Science and Engineering. We are connected to the main Spanish groups in this area, in the context of the "Sociedad Española de Métodos Numéricos en Ingeniería" (SEMNI), the "Sociedad Española de Matemática Aplicada" (SEMA) and the i-MATH Consolider Project.

We are collaborating with very prestigious international groups on Numerical Methods and Computational Mechanics (Ticam, Berkeley, Bonn, Delft, Nantes, Lieja, Pavia, Université Blaise Pascal, Santiago de Chile, Concepción, Bath, Edimburgh). The most important collaborations are the following: Department of Aeronautics & Astronautics del Massachusetts Institute of Technology (USA), Department of Civil Engineering de la University of Wales Swansea (UK), École Normale Supérieure de Cachan (Francia), Department of Mathematics and Institute for Physical Science and Technology, University of Maryland, Maryland (United States of America), Istituto di Analisi Numérica, Consiglio Nazionale delle Richerche, Pavia (Italia), Ecole National Supérieure d´Electricité et de Mécanique, Nancy (France), Laboratoire Jean Alexandre Dieudonné, Université de Nice (France), Universidad de Chile and Universidad de Concepción (Chile), University of Bath (U.K.) and Heriot-Watt University (U.K.).

During previous projects we have worked on building a bridge between the community of Numerical Methods for Environmental Applications and of Meteorological Phenomena Prediction. With this purpose, we have organized Special Sessions on Environmental Modelling in several national and international numerical methods conferences keeping the connection between both communities.

2 Summary of objectives of the project

- Realistic numerical simulation of wind fields (by using a mass consistent model and Navier-Stokes equations) over complex terrain and urban environment. Wind power prediction in local scale and wind maps construction.

- Air quality numerical modelling and forecasting at local scale, including urban environments. Three-dimensional adaptive numerical modelling of air quality transport-reaction equations.

- Data assimilation in forest fire spread models. Forest fires spread realistic predictions.

- Numerical modelling of solar radiation. Solar radiation maps construction. Solar radiation forecasting.

- Implementation and validation of efficient codes to be used by the EPOs in realistic applications

Several figures, obtained with our codes, are included in this section to illustrate the main objectives of the project: wind, solar radiation, air pollution and fire propagation; see figures 2-8.

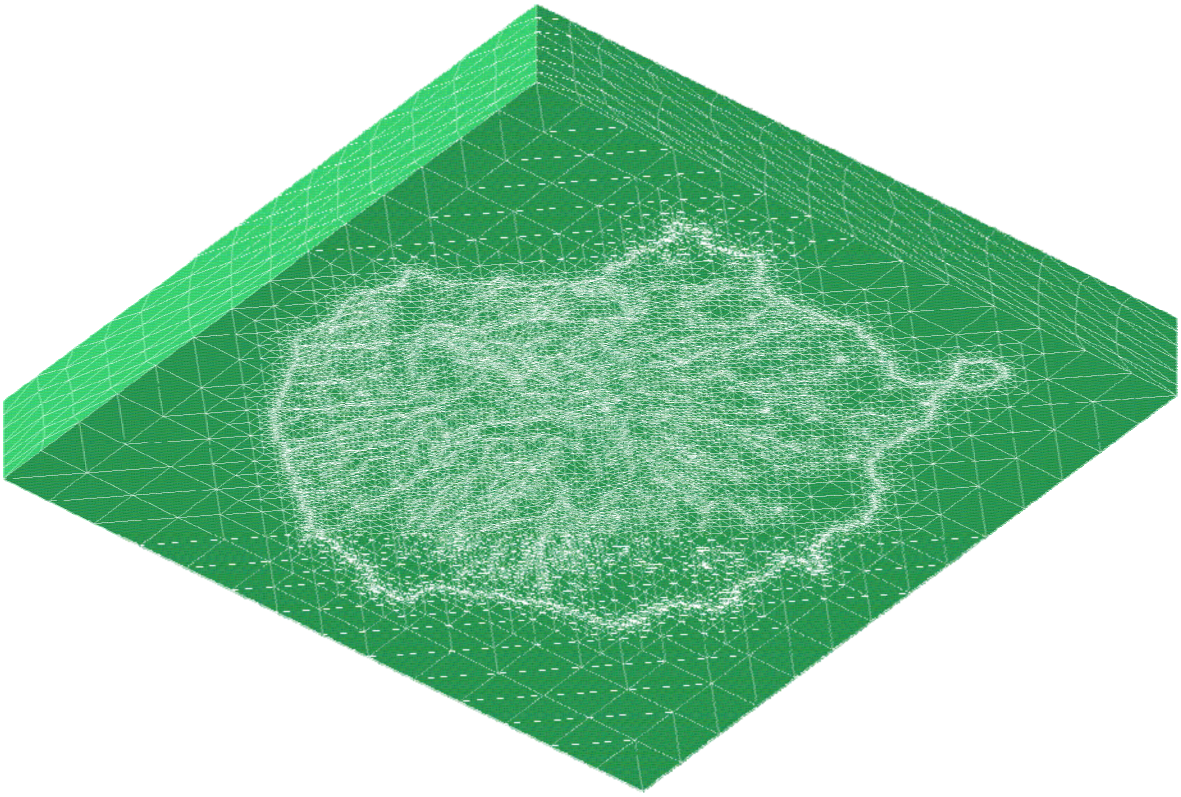
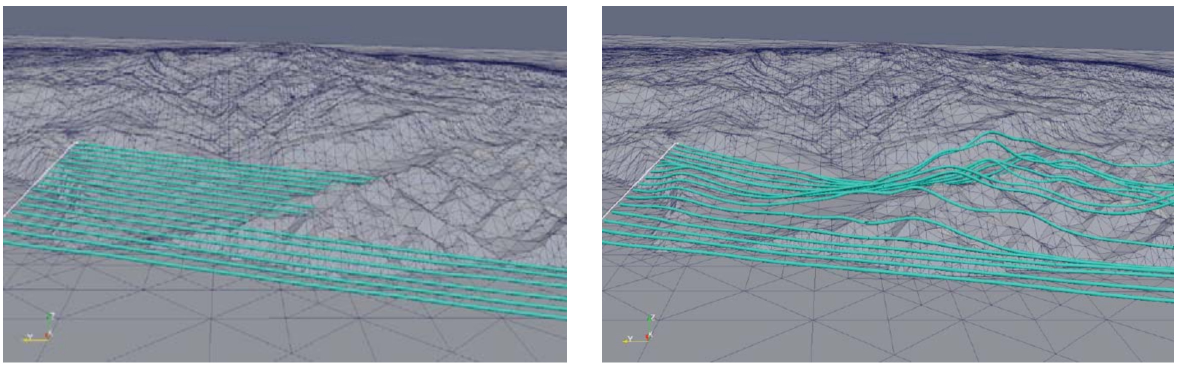


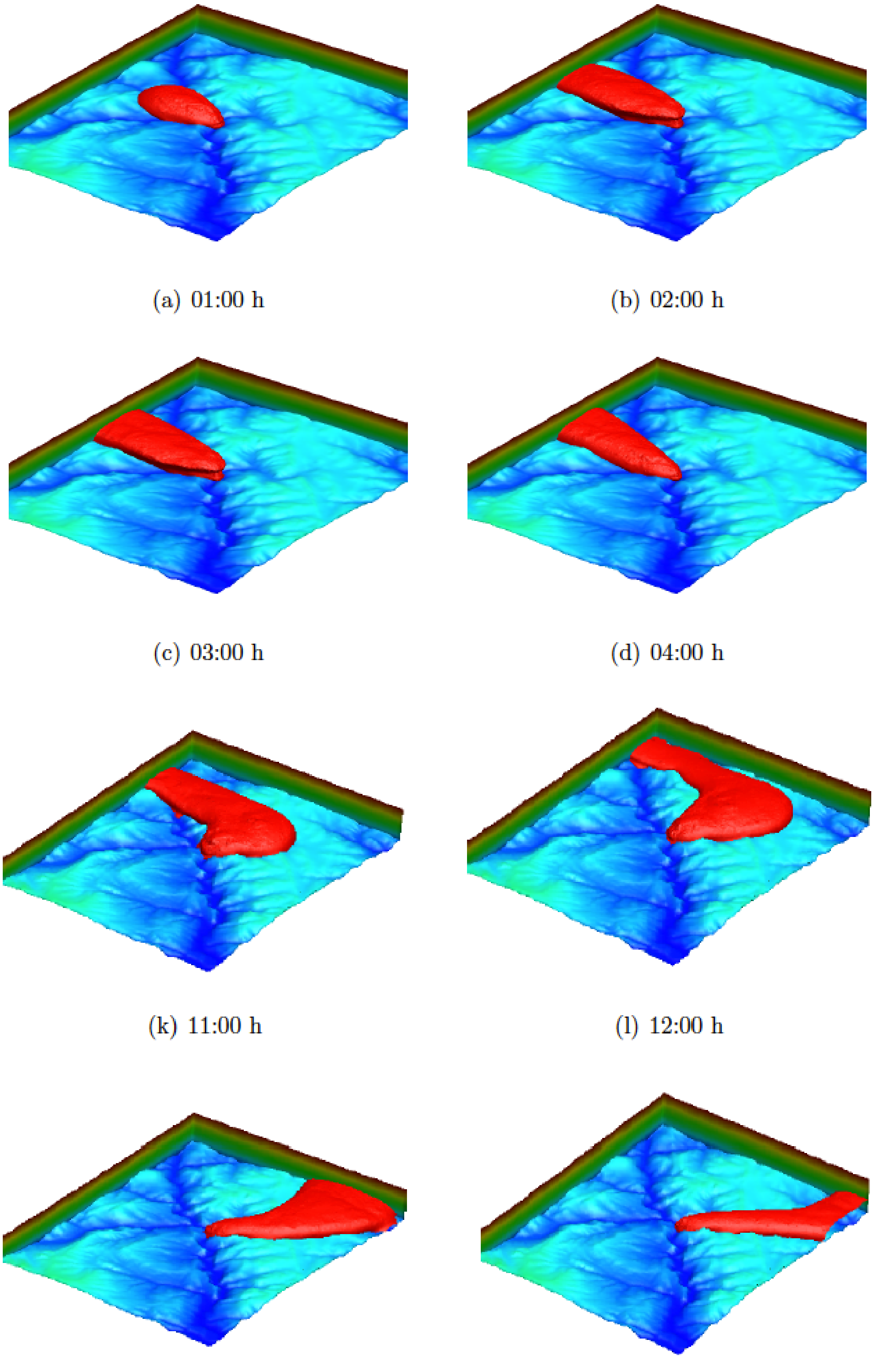
Figure 2: Three-dimensional mesh of Gran Canaria Island. The tetrahedral mesh has been generated by our codes and it is adapted to the terrain, coast line and on a circular region around control points.



(a) (b)

Figure 3: Application in Gran Canaria Island: detail of the streamlines of the interpolated wind from HARMONIE (a) and resultant wind obtained with the adaptive mass consistent model (b).

Figure 4: Three-dimensional “Earth-Atmosphere” tetrahedral mesh generated by the meccano method. This method has been developed by ULPGC and USA.



(a) 01:00 h

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(k) 11:00 h

(l) 12:00 h

(m) 13:00 h

(n) 14:00 h

Figure 5: Example of air quality simulation in La Oroya (Perú). Evolution of plume from 01:00 to 14:00 in a standard day (from the point of view of wind patterns).

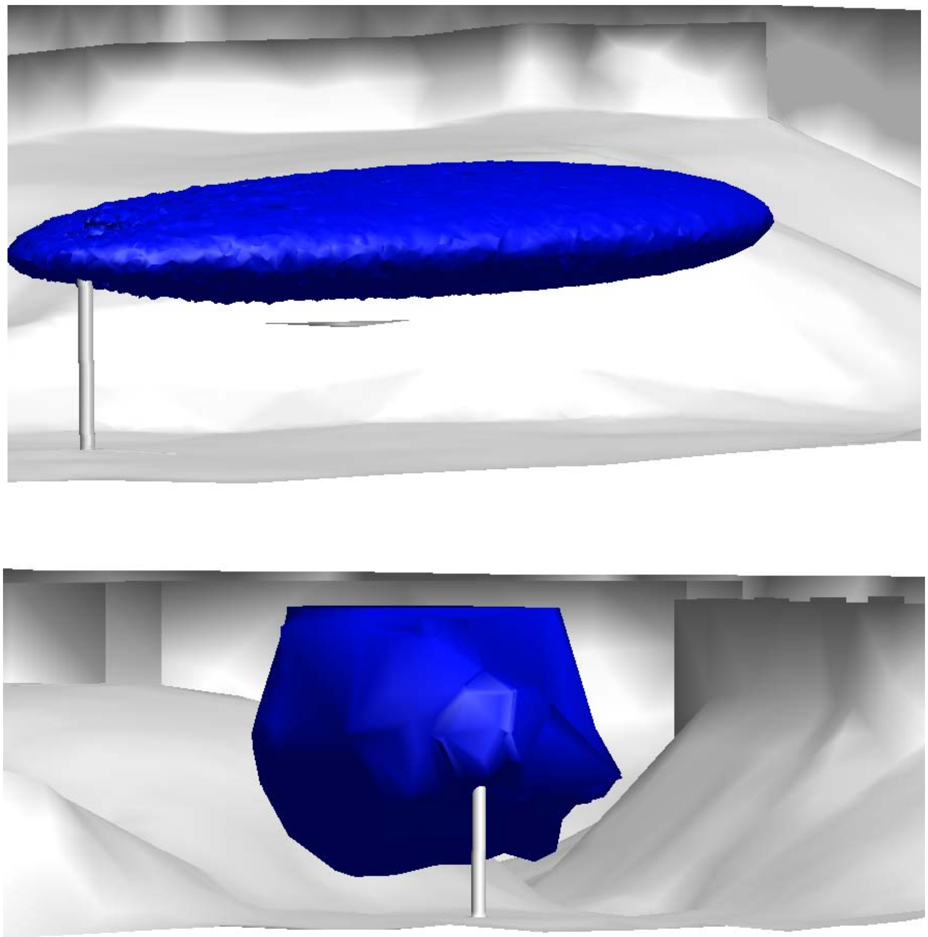

Figure 6: Example of plumes under different vertical diffusion parameters. Iso-surfaces for relative concentration equal to 10^{-3}.

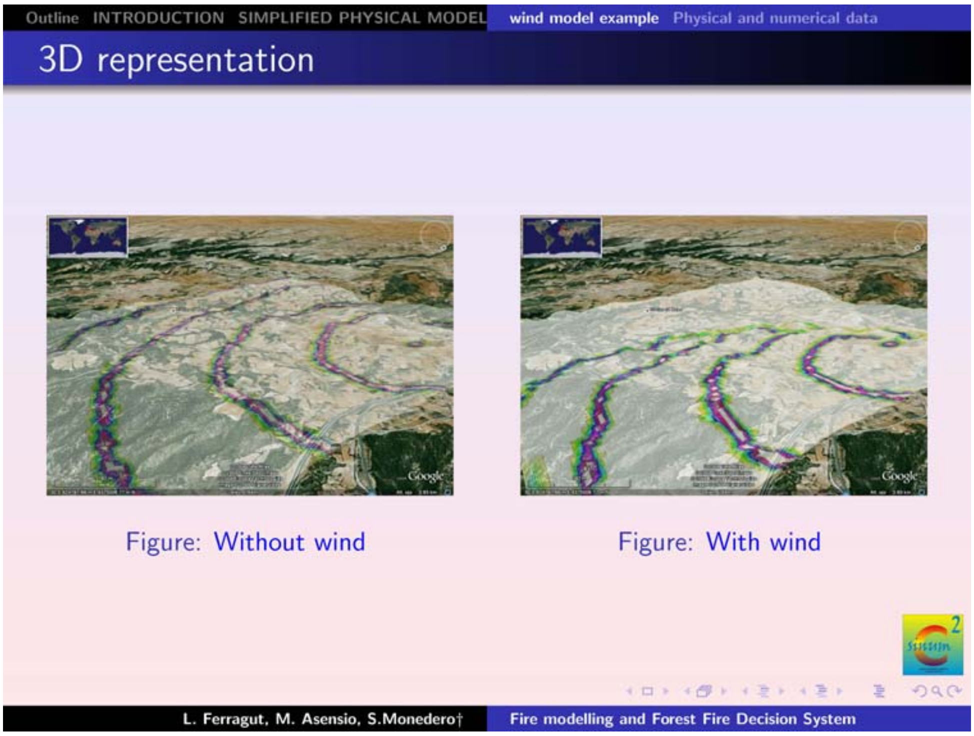

Figure 7: Application of the fire propagation model after 5 hours. Computation time 25 minutes.

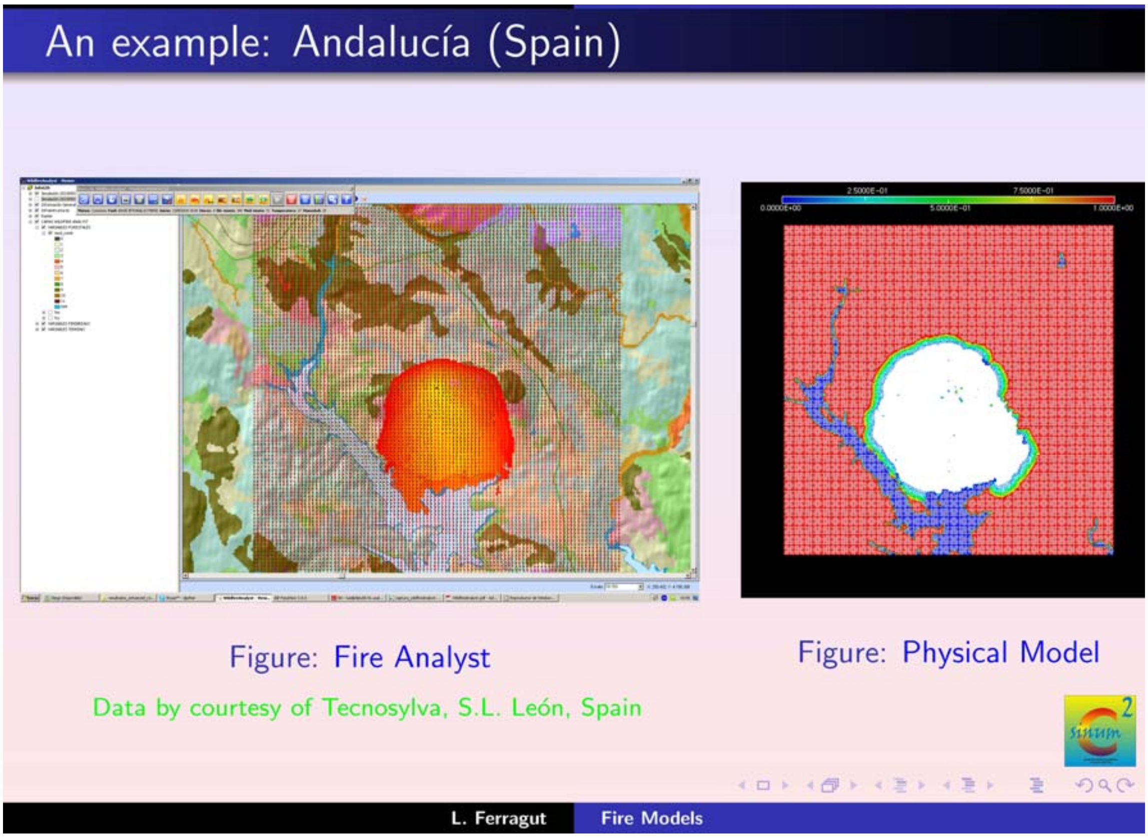

Figure 8: Region of Andalucía for the validation of the 2.5-D forest fire propagation model.