Simulation models for geospatial environmental problems

XXVI Congress of Differential Equations and Applications / XVI Congress of Applied Mathematics (XXVI CEDYA / XVI CMA)

M. I. Asensio-Sevilla[1], D. Prieto-Herráez[2], J. Manuel Cascón[3]

[1,2] Applied Mathematics Department, University of Salamanca, Casas del Parque 2, 37008 Salamanca, Spain
[3] Economy and Economic History Department, University of Salamanca, Building FES, Campus Miguel de Unamuno, 37007 Salamanca, Spain
[1,2,3] Fundamental Physics and Mathematics University Institute, University of Salamanca, Casas del Parque 1, 37008 Salamanca, Spain
[1] mas@usal.es, [2] dpriher@usal.es, [3] casbar@usal.es

Gijón, June 14-18, 2021

Introduction

The Research Group on Numerical Simulation and Scientific Calculation (SINUMCC) of the University of Salamanca is a multidisciplinary group dedicated to research in various aspects of numerical simulation and scientific calculation, with special interest in the area of environmental problems.

In this poster, we present three environmental models developed by SINUMCC:

- HDWind©: microscale wind field model.
- PhyFire©: simplified physical wildfire spread model.
- PhyNX©: air pollution model.

The solutions are approximated by using efficient numerical methods (Adaptive FEM, splitting method, reduced basis schemes, parallel computation). The three previous models are implemented using the Neptuno++© library, integrated into a geographic information system (GIS) and available on the web site: `http://sinumcc.usal.es`.

HDWind©

HDWind© is a mass-consistent vertical diffusion wind field model intended to provide a three-dimensional wind field by solving only two-dimensional linear equations. This model arises from an asymptotic approximation of the *Navier-Stokes* equations, on the assumption that the horizontal dimension of the domain is much greater than the vertical dimension.

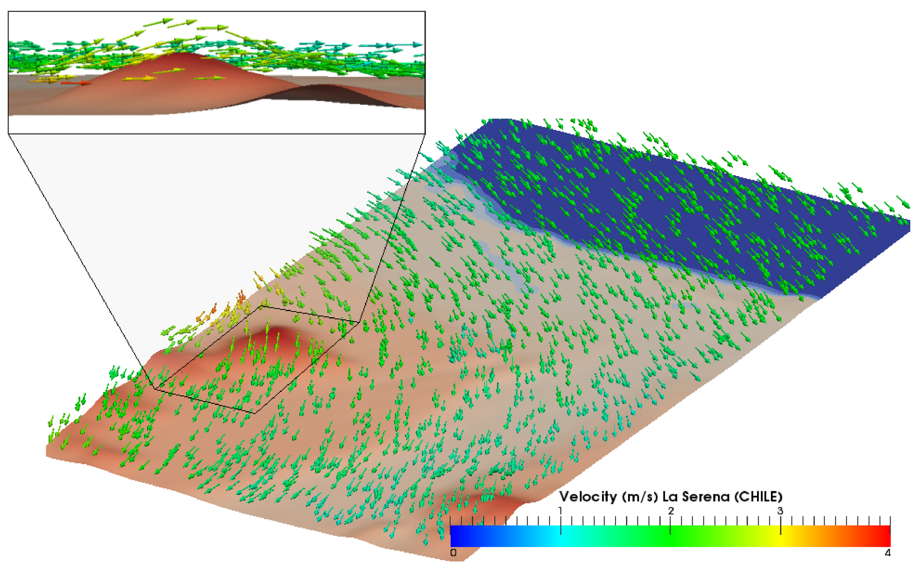
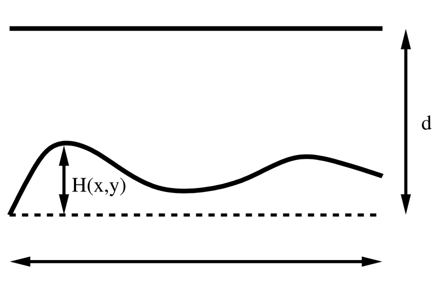


Figure 1 – Wind field computed by HDWind.

Among the effects that the HDWind model takes into account, we found the slope and roughness of the terrain, the temperature gradients on the surface and the conservation of mass stand out.

An asymptotic analysis of *Navier-Stokes equations*, assuming:

- d is small compared with L.
- Wind is not too strong $d^2\text{Re} \ll 1$.
- Temperature decreases linearly with the height.



yields the HDWind© equations:

$$\begin{aligned} -\partial^2_{zz}\mathbf{V} + \boldsymbol{\nabla}_{xy}P &= 0, \\ \partial_z P &= \lambda T, \\ \boldsymbol{\nabla}_{xy}\cdot\mathbf{V} + \partial_z W &= 0. \\ &+ \text{boundary cond.} \end{aligned}$$

The wind field solution is given by:

$$\mathbf{V}(x,y,z) = m(x,y,z)\boldsymbol{\nabla}_{xy}p(x,y) + n(x,y,z)\boldsymbol{\nabla}_{xy}T_S(x,y)$$

where $m(x,y,z)$, and $n(x,y,z)$ are coefficient that depends on $H(x,y)$ (orography) and d (air layer), T_S is the temperature on ground surface and $p(x,y)$ is solution of the 2D problem

$$\begin{aligned} -\boldsymbol{\nabla}_{xy}\cdot(a\boldsymbol{\nabla}_{xy}p) &= \boldsymbol{\nabla}_{xy}\cdot(b\boldsymbol{\nabla}_{xy}T_S) \quad \text{in } \omega, \\ a\boldsymbol{\nabla}_{xy}p\cdot\boldsymbol{\nu} &= -b\boldsymbol{\nabla}_{xy}T_S\cdot\boldsymbol{\nu} + (d - H(x,y))\mathbf{v}_m(x,y)\cdot\boldsymbol{\nu} \quad \text{on } \partial\omega. \end{aligned}$$

Here ω is projection of the three–dimensional and $\mathbf{v}_m$ the meteorological wind.

In practical applications, the wind field provided by the model adjusts to various point measurements of wind. This adjustment is made through the resolution of an optimal control problem in which the wind flow over the boundary is the control element.

For more information about the HDWind© model see: (FERRAGUT; ASENSIO; SIMON, 2011; PRIETO-HERRÁEZ; FRÍAS-PAREDES, et al., 2021).

PhyFire©

PhyFire© is a simplified physically based two-dimensional wildfire spread model based upon energy and mass conservation laws, that uses radiation and convection as dominant heat transfer mechanisms, and takes into account some three-dimensional effects. The model leads to a system of partial differential equations, solved with efficient numerical methods (FEM) that allows simulations in significantly less time than real.

Main wildfire spread features taken into account:

1. Influence of fuel moisture content and fuel type.
2. Energy transported by convection in the pyrolyzed gas (one-phase model).
3. Natural convection losses in vertical direction.
4. Flame tilt due to wind or terrain slope.
5. Thermal radiation by a non-local 3D radiation term.

Model equations:

$$\begin{aligned} \partial_\tau e + \beta\mathbf{v}\cdot\boldsymbol{\nabla}e + \alpha u = r + q &\quad \text{in } S \quad \tau \in (0,\tau_{max}), \\ e \in G(u) \quad \text{in } S &\quad \text{in } S \quad \tau \in (0,\tau_{max}), \\ \partial_\tau c = -g(u)c &\quad \text{in } S \quad \tau \in (0,\tau_{max}). \\ &+\text{boundary \& initial cond.} \end{aligned}$$

Model unknowns:

Unknown	Symbol	Units
Enthalpy	$E\ (e = E/MCT_\infty)$	$J\,m^{-2}$
Solid fuel temperature	$T\ (u = (T - T_\infty)/T_\infty)$	K
Solid fuel load	$M\ (c = M/M_0)$	$kg\,m^{-2}$

Model parameters:

Parameter	Symbol	Units
Mean absorption coeff.	$a\,(in\,r)$	m^{-1}
Natural convection coeff.	$H\,(in\,\alpha)$	$J\,s^{-1}\,m^{-2}\,K^{-1}$
Convective term factor	β	–

Model terms:

- $\boxed{\beta\mathbf{v}\cdot\nabla e}$: Energy convected by the gas pyrolyzed.
- $\boxed{\alpha u}$: Energy lost by natural convection in the vertical direction.
- $\boxed{r}$: Non-local radiation.
- $\boxed{q}$: Fire-spotting (random term).
- $\boxed{G(u)}$: Multivalued operator: fuel moisture content effect.
- $\boxed{g(u)}$: Loss of solid fuel due to combustion.

In addition, it incorporates a set of variables that allows estimating the magnitude of the energy released during combustion for each type of fuel:

Input variable	Symbol	Units
Maximum fuel load	M_0	$kg\,m^{-2}$
Moisture content	M_v	kg water/kg fuel
Flame temperature	T_f	K
Pyrolysis temperature	T_p	K
Combustion half-life	$t_{1/2}$	s
Flame length indep. factor	F_H	m
Flame length wind corr. factor	F_v	$m^{1/2}\,s^{1/2}$
Flame length slope corr. factor	F_s	–
Heat capacity	C	$J\,K^{-1}\,kg^{-1}$

For more information about the PhyFire© model see: (PRIETO-HERRÁEZ; ASENSIO; FERRAGUT; CASCÓN, 2015; ASENSIO; MARTÍN, et al., 2020; ASENSIO; FERRAGUT, et al., 2020).

PhyNX©

PhyNX© is an air pollutant dispersion model that describes convection, turbulent diffusion, and emission.

Among its main characteristics, stand out:

1. A non-reactive urban scale Eulerian multilayer air pollution model.
2. Takes into account convection, turbulent diffusion and emission.
3. Assume a Gaussian model to determine the diffusivity coefficients.
4. Coupled with the HDWind© mass-consistent wind field model.

The convection-diffusion equation of the model is:

$$\partial_t C + \mathbf{V}\cdot\boldsymbol{\nabla}_{xy}C + W\partial_z C - \boldsymbol{\nabla}_{xy}\cdot(K_h\boldsymbol{\nabla}_{xy}C) - \partial_z(K_v\partial_z C) = f.$$
$$+\text{boundary \& initial cond.}$$

where:

- C is pollutant concentration.
- $K_h = K_{xx} = K_{yy} = \frac{\sigma_h^2\|\mathbf{U}\|}{2r}$ are horizontal diffusion coefficients.
- $K_v = K_{zz} = \frac{\sigma_v^2\|(\mathbf{V},W)\|}{2r}$ are vertical diffusion coefficients.
- $(\mathbf{V},W) = (U_1,U_2,U_3)$ is the wind (HDWind© model).
- f source term.

The air is assumed initially clean, $(C(t=0,\cdot)=0)$ and the loss of pollution on the outdoor boundary is supposed exclusively through lateral boundary (no loss on upper and lower boundary).

Under an appropriate change of coordinates, the previous problem is rewritten into a **cuboid** that is discretized using prisms with triangular sections and constant height. This strategy allows to apply an efficient numerical method, whose main features are:

1. 2D- adaptive FEM with characteristics in each horizontal direction (layers).
2. FD method in vertical direction (first order upwind scheme for convective terms and second-order central difference for diffusive ones).
3. Splitting techniques to solve the problem in each air layer separately.
4. Unconditionally stable numerical scheme.
5. Parallel computation.

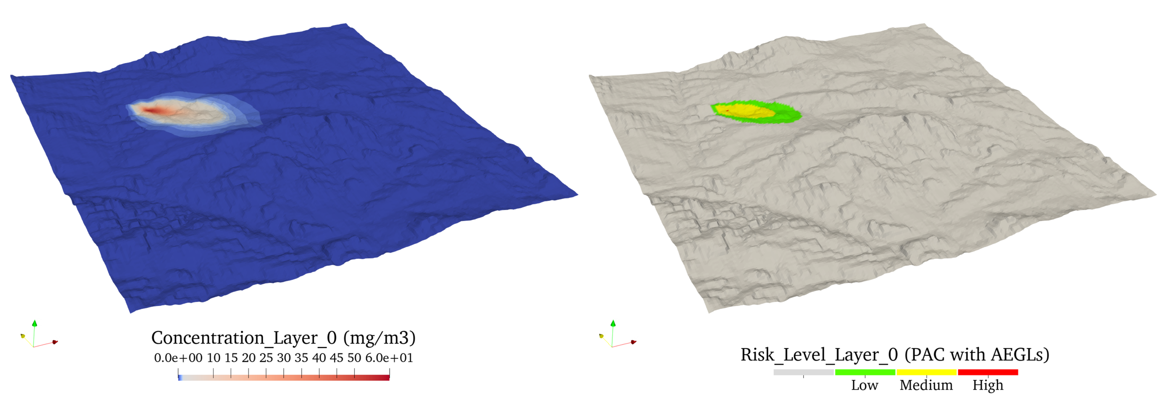


Figure 2 – Simulation with PhyNX of the atmospheric dispersion of a hypothetical continuous emission of a non-reactive gas. AEGL hazard levels (left) and concentration (right).

For more information about the PhyNX© model see: (FERRAGUT; ASENSIO; CASCÓN, et al., 2013).

HDWind SINUM · PhyFire SINUM · PhyNX SINUM

The GIS interfaces

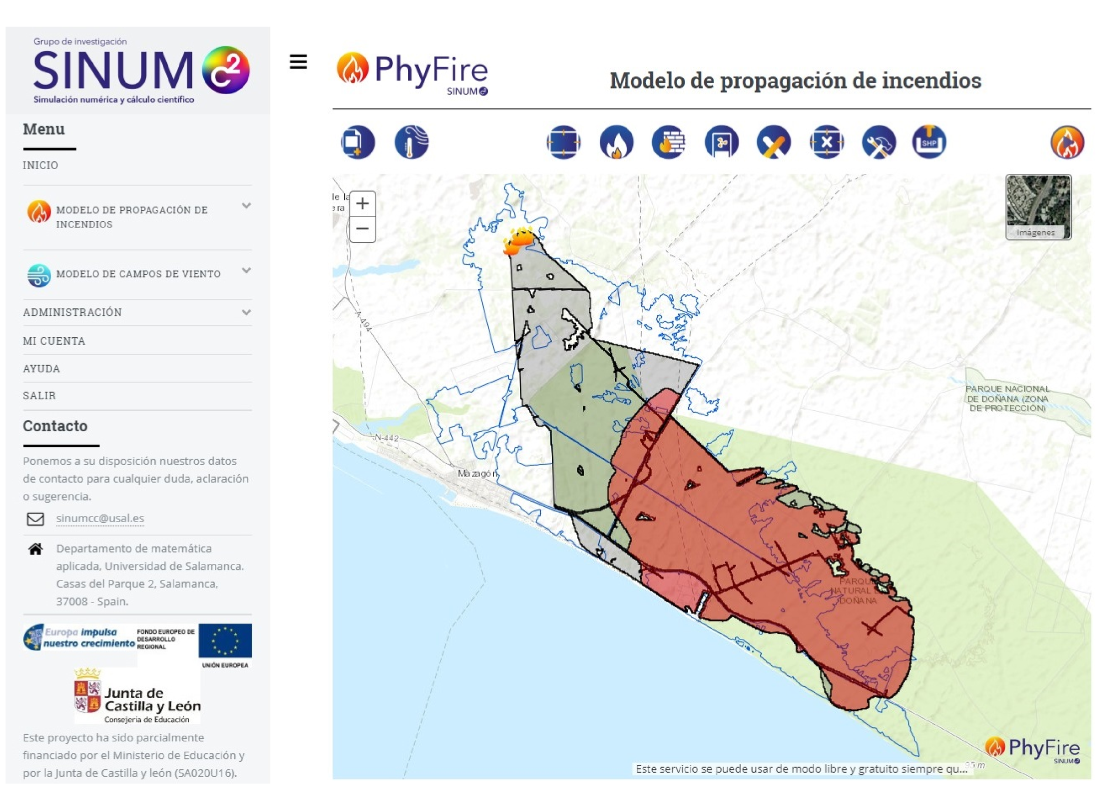


Figure 3 – Portal Web GIS with access to the developed environmental models.

The three models have been integrated into a GIS environment so that the geospatial data needed to perform a simulation are provided to the models by a GIS application.

This integration has been done both on a desktop application (as an add-in for the ArcMap application), on a cloud environment thought the development of a Server Object Extension for ArcGIS Server, which is available in https://sinumcc.fis.usal.es, and even in an android application that allows the execution of the environmental models from a mobile terminal.

This integration in the GIS environment allows:

- To provide a simple, intuitive and easy-to-use tool.
- To make the models accessible to a broader non specialist audience.
- To automate data acquisition.
- To pre-process geographical information.
- To reduce simulation time.
- To prevent input data errors.

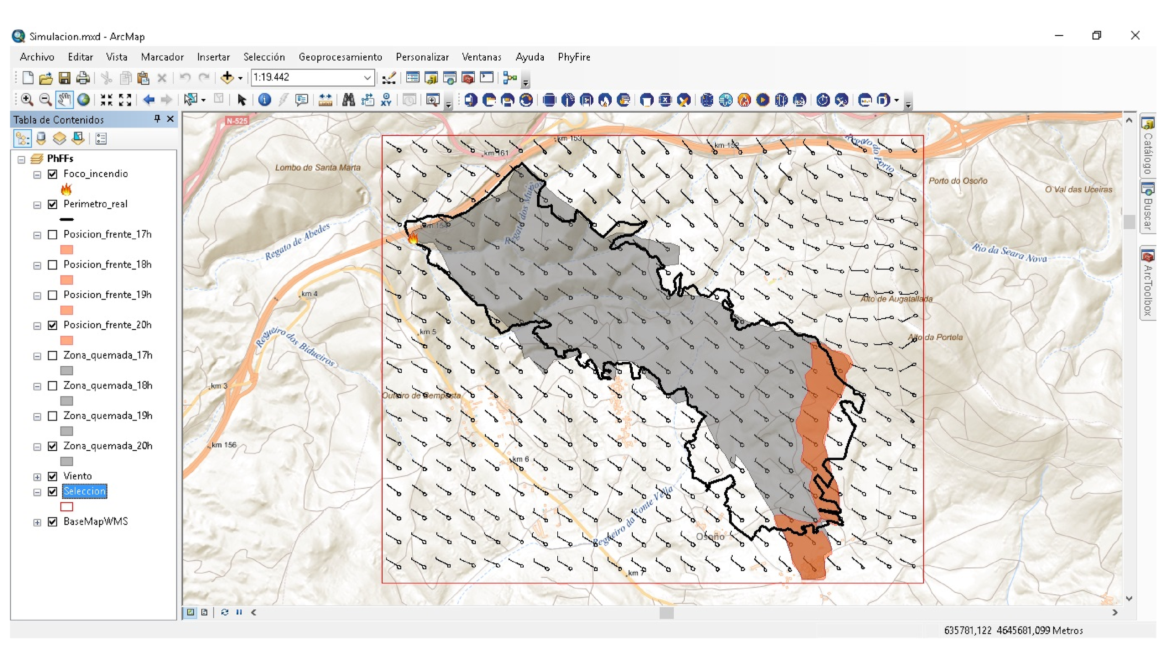


Figure 4 – Add-in for the ArcMap application with access to the developed environmental models.

For more information about the GIS integration of these environmental models see: (PRIETO-HERRÁEZ; ASENSIO; FERRAGUT; CASCÓN; MORILLO, 2017; ASENSIO; FERRAGUT, et al., 2020).

Acknowledgments

This work has been partially funded by the European Regional Development Fund (ERDF) (Grant contract SA089P20):

Universidad de Salamanca · Junta de Castilla y León · Europa impulsa nuestro crecimiento · Fondo Europeo de Desarrollo Regional · Unión Europea

References

ASENSIO, M. I.; FERRAGUT, L., et al. PhyFire: An Online GIS-Integrated Wildfire Spread Simulation Tool Based on a Semiphysical Model. In: ASENSIO, M.; OLIVER, A.; SARRATE, J. (Eds.). **Applied Mathematics for Environmental Problems**. [S.l.]: Springer Series, 2020. v. 6. (SEMA SIMAI). chap. 1, p. 1–20. ISBN 978-3-030-61795-0. DOI: `10.1007/978-3-030-61795-0_1`. Available from: ↗.

ASENSIO, M. I.; MARTÍN, M. T. S., et al. Global sensitivity analysis of fuel-type-dependent input variables of a simplified physical fire spread model. **Mathematics and Computers in Simulation**, v. 172, p. 33–44, 2020. ISSN 0378-4754. DOI: `https://doi.org/10.1016/j.matcom.2020.01.001`. Available from: ↗.

FERRAGUT, L.; ASENSIO, M. I.; CASCÓN, J. M., et al. An efficient algorithm for solving a multi-layer convection–diffusion problem applied to air pollution problems. **Advances in Engineering Software**, Elsevier Science Limited, v. 65, n. 100, p. 191–199, 2013. ISSN 0965-9978. DOI: `https://doi.org/10.1016/j.advengsoft.2013.06.010`. Available from: ↗.

FERRAGUT, L.; ASENSIO, M. I.; SIMON, J. High definition local adjustment model of 3D wind fields performing only 2D computations. **International Journal for Numerical Methods in Biomedical Engineering**, John Wiley & Sons, Ltd., v. 27, n. 4, p. 510–523, 2011. ISSN 2040-7947. DOI: `10.1002/cnm.1314`. Available from: ↗.

PRIETO-HERRÁEZ, D.; ASENSIO, M. I.; FERRAGUT, L.; CASCÓN, J. M. Sensitivity analysis and parameter adjustment in a simplified physical wildland fire model. **Advances in Engineering Software**, Elsevier Science Limited, v. 90, n. 100, p. 98–106, 2015. ISSN 0965-9978. DOI: `https://doi.org/10.1016/j.advengsoft.2015.08.001`. Available from: ↗.

PRIETO-HERRÁEZ, D.; ASENSIO, M. I.; FERRAGUT, L.; CASCÓN, J. M.; MORILLO, A. A GIS-based fire spread simulator integrating a simplified physical wildland fire model and a wind field model. **International Journal of Geographical Information Science**, Taylor & Francis, v. 31, n. 11, p. 2142–2163, 2017. ISSN 1365-8816. DOI: `10.1080/13658816.2017.1334889`. Available from: ↗.

PRIETO-HERRÁEZ, D.; FRÍAS-PAREDES, L., et al. Local wind speed forecasting based on WRF-HDWind coupling. **Atmospheric Research**, v. 248, p. 105219, 2021. ISSN 0169-8095. DOI: `https://doi.org/10.1016/j.atmosres.2020.105219`. Available from: ↗.