High resolution wildfires simulation, forecasting tools to estimate front evolution, fire induced weather and pollution

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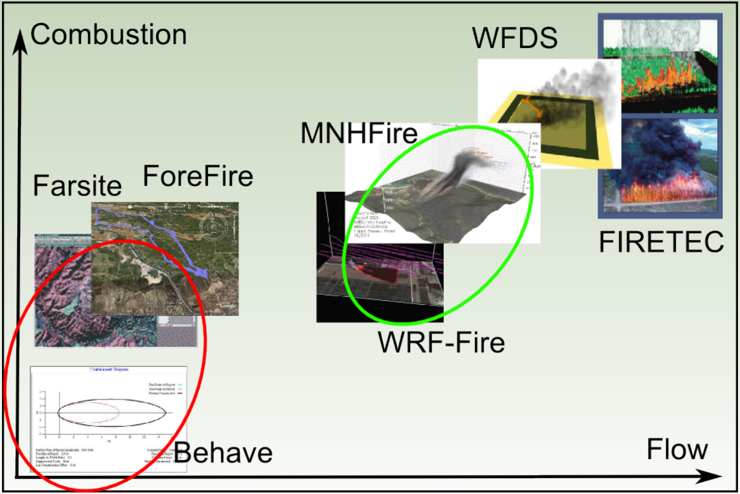
Very large fires

- Multi-physics, multi-scale problem :
  - combustion, emissions,
  - radiation/fluid dynamics,
  - atmospheric physics.
- Inhomogeneous boundary conditions :
  - atmosphere,
  - fuel,
  - elevation.

Approach

- High resolution fuels (sub-meter),
- reduced front velocity model,
- front tracking method,
- micro scale atmospheric model,
- fluxes as sub-mesh parametrization.

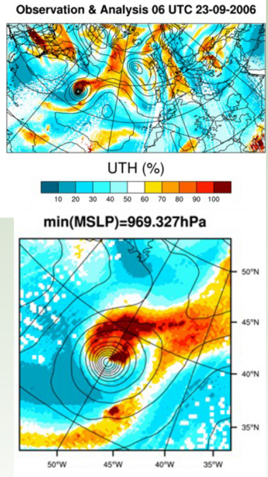
Wildland fire code ecosystem



Models and Codes

Meso-NH

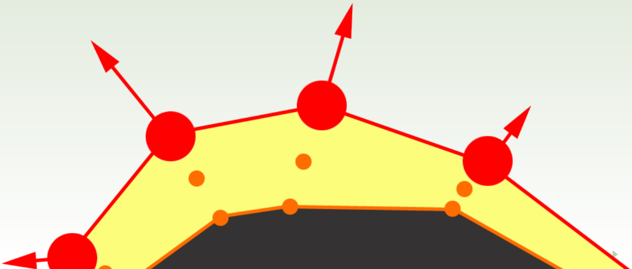
- GPL (CECILL)
- mesonh.aero.obs-mip.fr/mesonh51
- Météo-France/CNRM/LA
- Non-Hydrostatic anelastic,
- LES resolution (3D sub-grid TKE),
- Piecewise Parabolic Method
- explicit leapfrog scheme,
- two-way nesting,
- curvilinear grid,
- Fluxes type boundary condition (SURFEX surface module)



Lagrangian front tracking

Resolution problem : Asynchronous front tracking method

- Active nodes,
- sub meter resolution for extinction,
- dynamic addition and removal of markers,
- front depth λ diagnostic,
- filtering distance for interface refinement, p_r
- no explicit time step (event scheduler),
- Integration in space (CFL constant adaptive time step)



Balbi front velocity model

Fuel

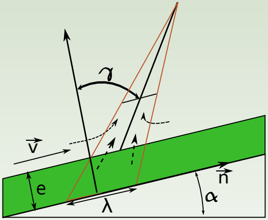
- Mass load σ
- height e
- emissivity ϵ_v
- moisture content m
- ignition temperature T_i
- heat capacity $c_{p,v}$
- combustion enthalpy Δh

Flame

- Stoichiometry s
- Pyrolysis mass loss rate $\dot{\sigma}$
- Radiant fraction χ_0
- Front depth λ, curvature K
- Normal wind $(\vec{v}.\vec{n})$ tilts flame γ
- Front velocity (Rate of spread) R

$$R = R_0(\epsilon_v, T_i, e, \sigma, m, T_a) + (1 + \cos K)\chi_0 \Delta h \dot{\sigma} f(\lambda, \gamma)$$

$$\tan\gamma = \tan\alpha + \rho_a(\vec{v}.\vec{n})/2(1+s)\dot{\sigma}$$

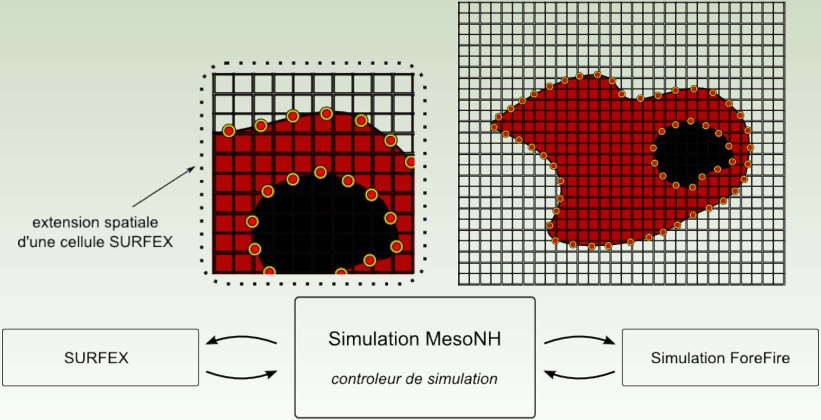


$$f(\lambda, \gamma) = \frac{\lambda}{2 + \mu\lambda\cos\gamma}(1 + \sin\gamma - \cos\gamma)\mathcal{H}_{\mathbb{R}^+}(\gamma)$$

Coupling fronts and atmosphere

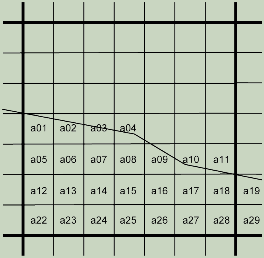
Coupling strategy

- Pronostic fronts
- Diagnostic fluxes



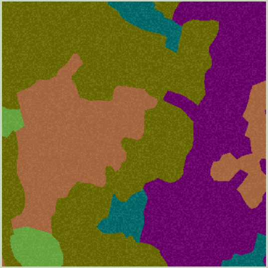
Burning map

- Time of first marker occurrence,
- polygon filling method,
- updated locally at each marker update.



Fluxes layers

- One layer for each variable, compound,
- diagnosed as a function of actual and arrival time



Sub-mesh integration - Combustion and emissions

Integration of local fluxes

$$\Phi^{\text{atmo}}(t) = \int_{\mathcal{I}_c} \Phi(\mathbf{x}, t),$$

- Flux model Φ at fire resolution $\mathcal{I}_c$
- Subgrid resolution Δx^{at} typically $< 1m$

Different fluxes models for each variables

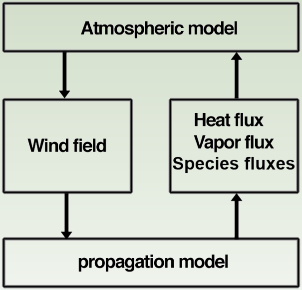
- Gamma approximation :

$$\Phi(\mathbf{x}, t) = \chi_b^0 exp(-4m/m_e)\Phi_{\mathbf{x}}^t$$

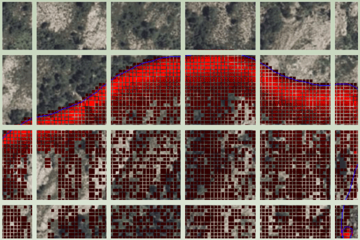
- Or constant during time τ (burning time) :

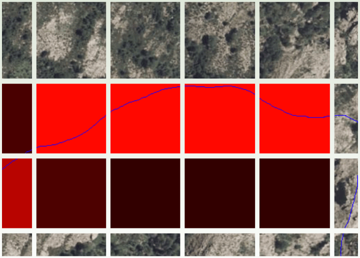
$$\Phi(\mathbf{x}, t) = \frac{\Phi_{\mathbf{x}}^t}{\tau}\Pi_{[0,1]}(\frac{t - t^a(\mathbf{x})}{\tau})$$

- $\Pi_{[0,1]}$ gate function on interval [0, 1],
- $\Phi_{\mathbf{x}}^t$ total heat,water, SO2 ... released



View in real Fire

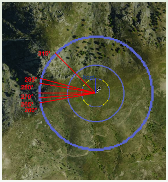




Simulation

Letia experiment

- Use of a LIDAR on field experiment
- Heat flux, flame and plume analysis



Letia experiment - Simulation

View Video

Similation Letia experiment + Lidar Scan

Smoke plume structure

- Domain size : 2.5 km x 2.5 km x 1.5 km ($\Delta x = 50m$), homogeneous mediterranean schrubs
- Similarities in observed/simulated structures(LES simulation, smoke passive tracer)

Ozone titration

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Effect of CO injection, coupled chemistry : ozone depletion in the plume

Fireflux experiment

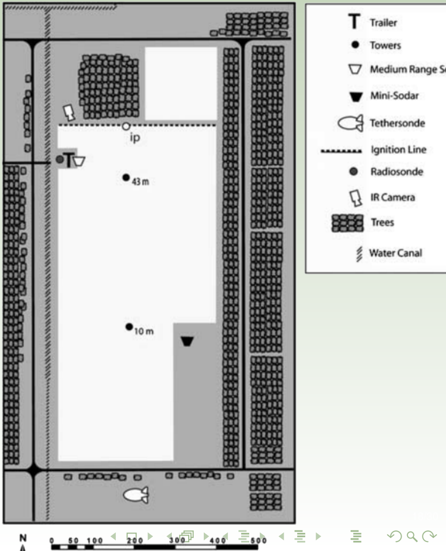
Grass fire

Experiment

- Experiment by Clements et al,
- 400 by 800 meters
- tall grass (1 meter),
- 10m / 25m atmo resolution,
- first grid cell height : 2m.
- fuel loading $\sigma = 1.08 kg.m^{-2}$
- nominal heat fluxes about $315 KW.m^{-2}$

Numerical parameters

- Width 1000m, height 300m,length 2000m
- Open boundary condition, relaxation over 6 top mesh cell
- initial condition from radio-sounding
- Filtering distance $p_r = 0.5m$



FireFlux simulation

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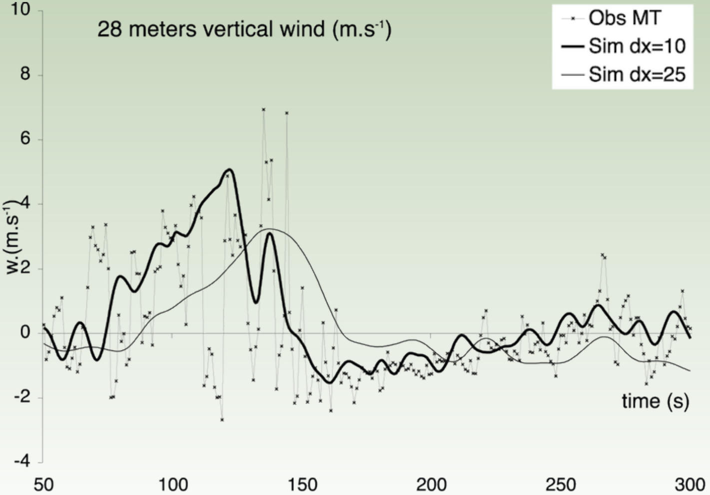
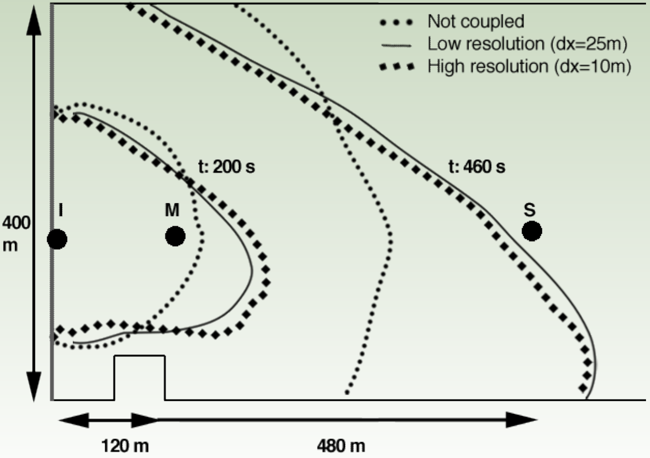
Fireflux 10m resolution ForeFire/MesoNH

28 meters height vertical wind



Arrival time

Tower passing times isochrones, Acceleration due to fire coupling.



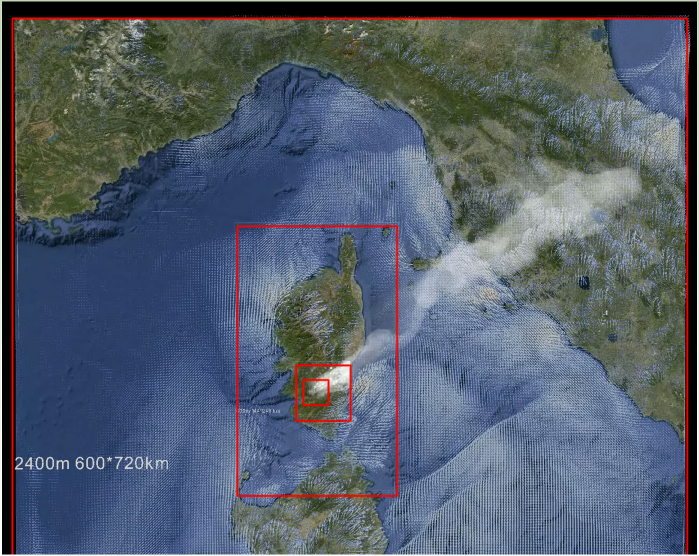
Valle Male Fire

Large Wildfire (3000Ha total, 2000 simulated)

- July 2009,
- 50/200/600/2400m nested atmospheric resolution,
- 0.1 / 10m front resolution,
- 5m fluxes resolution,
- Injection of heat, water,
- 24 millions gridpoints (64 levels)

	Tstep (s)	XY	XY (m)	CPU	Tsim	TexecIO	TexecComp
Mod1	6	250*300	2400	200	6h	27’	20’
Mod2	1.5	240*400	600	512	3h	28’	50’
Mod3	0.5	240*240	200	256	3h	4h20	2h
Mod4	0.25	300*300	50	900	10h	10h	8h

4 nested models



Valle Male Fire

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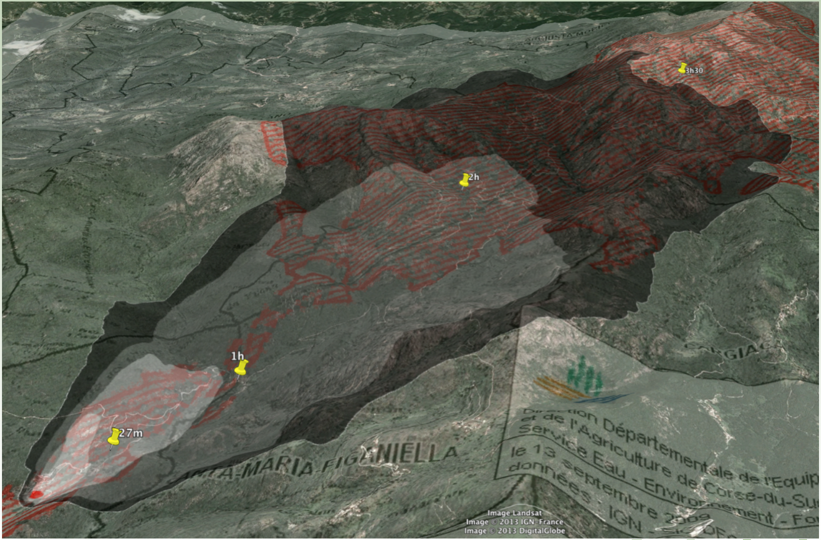
Combustion to the atmosphere, Valle Male Fire. IDEA large simulation

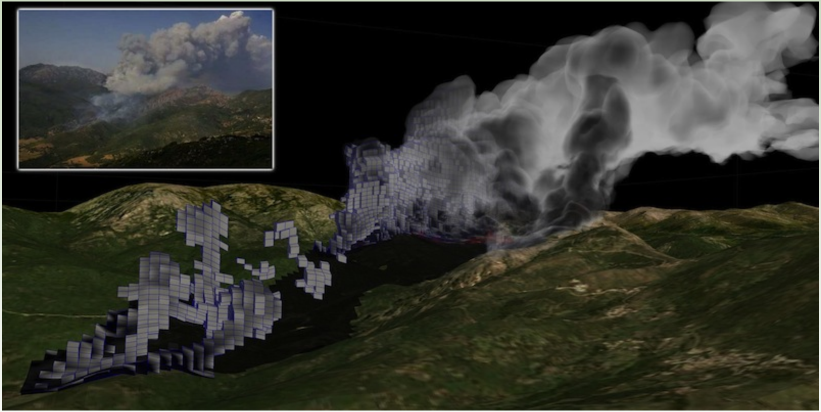
Valle Male Fire

Isochroneous simulated (grey) ; reported (yellow)



Valle Male Fire

Observed/simulated plume

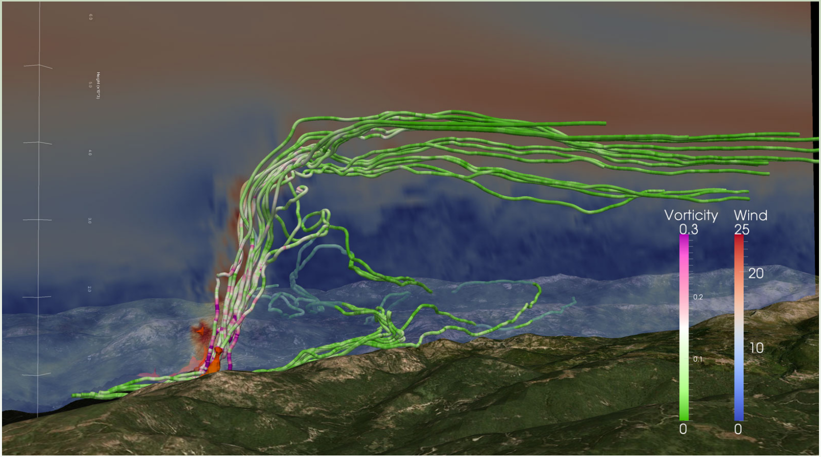


Valle Male Fire

MODIS / Simulation

Valle Male Fire

Vorticity on streamlines



Conclusion

Summary

- Fire code has been coupled to a mesoscale atmospheric model Meso-NH for lava/wildfire simulation),
- MesoNH/LES seems to capture well at high resolution
  - induced wind, convection,
  - plumes, smoke distribution,
- parallel version run real time on a large number of processors,
- good agreement with observed amplitudes and slower fluctuations.

Problems

- Lagrangian code not rock solid...
- May require better fluxes models

Perspectives

- More simulations with chemistry,
- Fuel maps and fuel models derived from surface !

Merci

ANR-09-COSI-006 http://anridea.univ-corse.fr