High resolution modeling of fires within the Euro-Mediterranean region

Jean Baptiste Filippi (CNRS SPE. University of Corsica, Corte, France) and Céline Mari (CNRS LA, Observatoire Midi-Pyrénées, Toulouse, France)

Introduction

Wildfires release significant amounts of trace gas and aerosols into the atmosphere. Firefighters are exposed to wildland fire smoke with adverse health effects. At larger scale, depending on meteorological conditions and fire characteristics, fire emissions can efficiently reduce air quality and visibility, even far away from emission sources. Uncertainties in fire emissions and fire plume dynamics are two important factors which substantially limit the capability of current models to predict smoke exposure and air quality degradation. The approach developped here is to develop very high (50 meters) resolution models to explicitely resove these plumes and emission in order to better numerically understand and estimate these phenomenons.

A collaborative effort recently started in France to develop a coupled fire-atmosphere model based on the fire propagation model ForeFire, developed at the University of Corsica, and the mesoscale non-hydrostatic meteorological model Meso-NH, developed by the University of Toulouse and Meteo-France. ForeFire is a semi-physical model based on an analytical estimation of the rate of spread and an integration with a front tracking method.

Wildfire coupled model

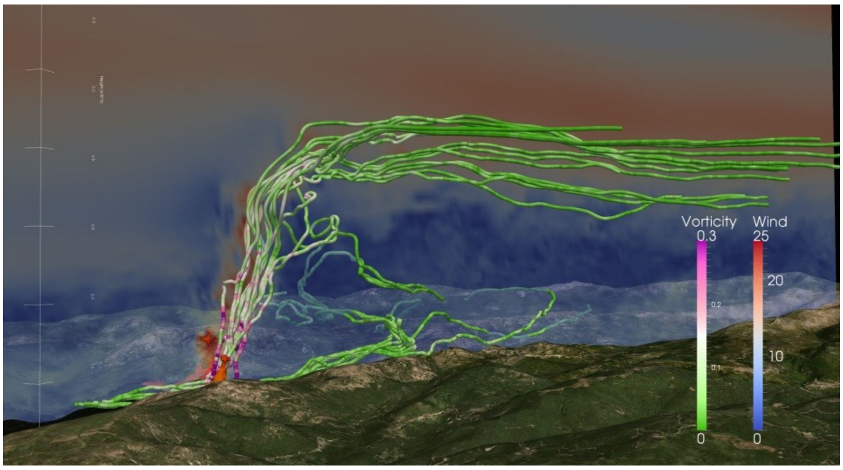
To be representative of the phenomenon, typical resolution required for the simulation of a fire front or a lava flow is sub-meter (to have an explicit flame depth or narrow flow width) while atmospheric simulation of a typical domain (several tens of square kilometres) may not be performed at a resolution of finer than 50 meters in a reasonable computational time. Front tracking is performed by means of Lagrangian markers that allow simulating interface dynamics at high spatial resolution, temporal scheme is event based with a Courant–Friedrichs–Lewy constant time step calculated for each marker iteration, allowing efficient simulation focused on active flow areas.

The Lagrangian front dynamics is used to construct a "time of arrival" high-resolution field that is used to perform local budgets of the different surface fluxes models in a way similar to the level-set method. The two way coupling in a Meso-NH/ForeFire simulation typically involve the surface wind to drive the fire, and heat and water vapour fluxes to be injected in the atmosphere at each atmospheric time step. The ForeFire code has been built so that several front velocity function could be easily defined and applied at different locations of the surface (e.g. a fire front velocity model could be different in forest with canopy than in grassland), likewise surface fluxes models (combustion) can be added and defined in the same way, superposed as surface layers with each layer corresponding to an energy, mass or species flux that will be forced in the atmospheric model.

Meso-NH and ForeFire resolutions are independent and the computational time needed by the surface model is a typically a fraction of the atmospheric simulation. Parallel strategy for the surface model mimics the one in the atmosphere model (with Lagrangian markers sent between parallel sub-domains), thus recovering the parallel efficiency of the atmospheric optimized parallel design.

Simulations

In order to estimate the opportunity to use this coupled code, high-resolution simulations on wildfire experiments was performed and presented better possible diagnostics (atmospheric flow) than non-coupled simulations [Leroy et. al. 2013] [Filippi et. al. 2011, 2013a, 2013b]. The simulation of the large 2009 3000 Ha Aullène fire (Corsica Island, France) show that computations can be performed at large scale in a reasonable computational time and a good overview of the large structures presents within the plume (see figure).



Simulation of the Aullene fire at 15h20. Lines correspond to particle trajectories if they were lift from the ground, colored by their rotating tendency. The red area corresponds to the simulated hot air envelope and velocity around the flame.

The coupled model was used then used specifically for atmospheric compositions with online chemistry model activated [Strada 2012]. Simulations were performed in two configurations depending on the spatial resolution: with or without the feedback of the atmosphere on the fire propagation.

At kilometric resolution, the model was used off-line to simulate two Mediterranean fires: an arson wildfire that burned in 2005 near Lancon-de-Provence, south-eastern France, and a well documented episode of the Lisbon 2003 fires (in collaboration with the University of Aveiro, Portugal). The question of the injection height is treated with an adaptation of the eddy-diffusivity/mass flux approach for convective boundary layer and compared to the 1D Plume Rise Model (developed at INPE) in contrasted meteorological scenarios. At higher resolution, the two-way coupled model was tested on idealized and real fire cases including ozone chemistry showing reasonable agreements with observation [Strada 2012].

Current developpements are focused on coupled lava flow/atmosphere simulations and on surface emissions and combustion chemistry models.

Acknowledgements

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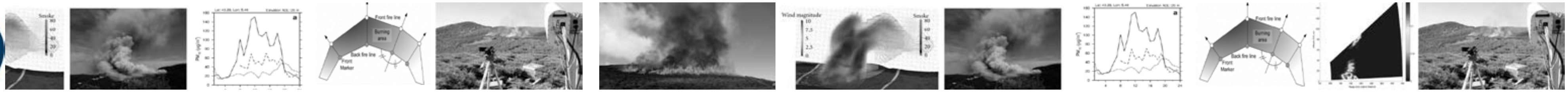

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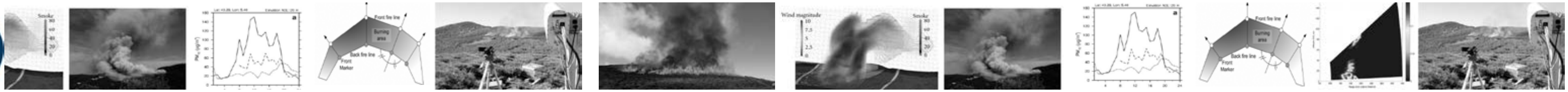


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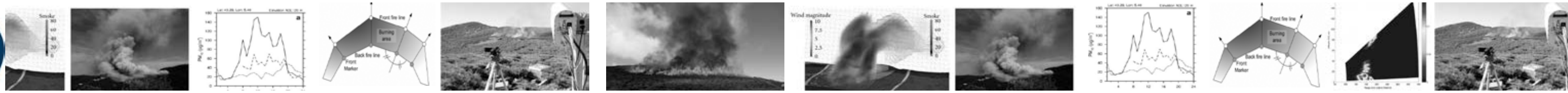
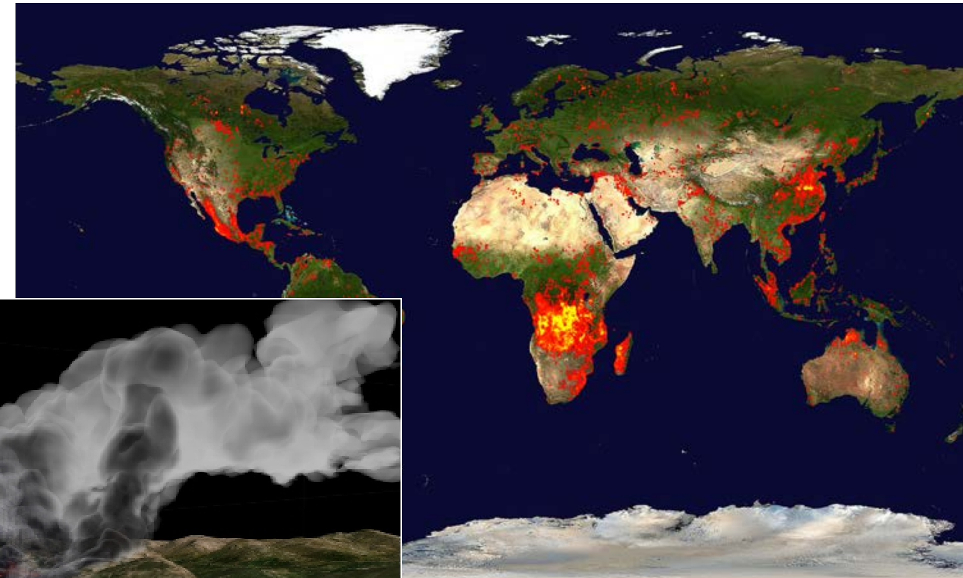
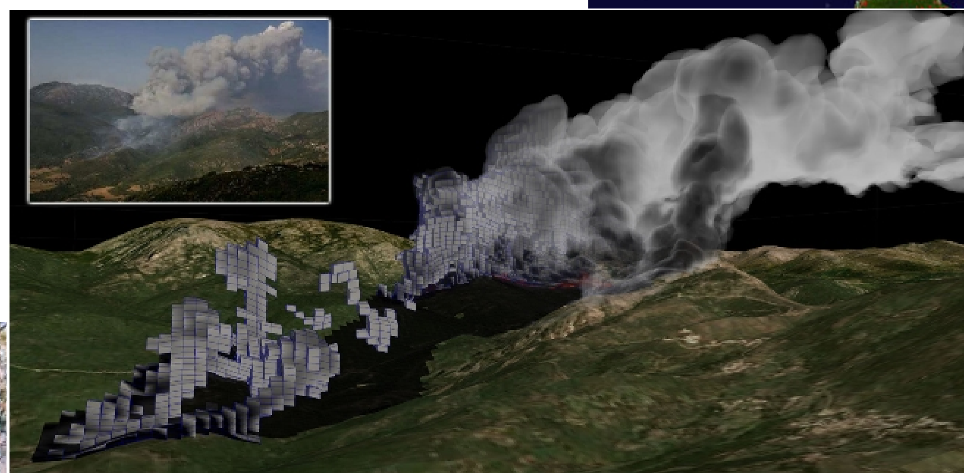


Multiscale processes



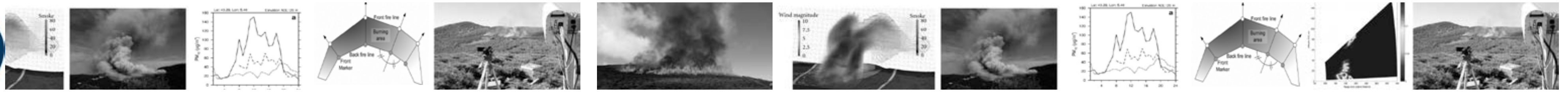
Global impacts



Fire-atmosphere interactions

Fire behavior

Flame scale



Fires

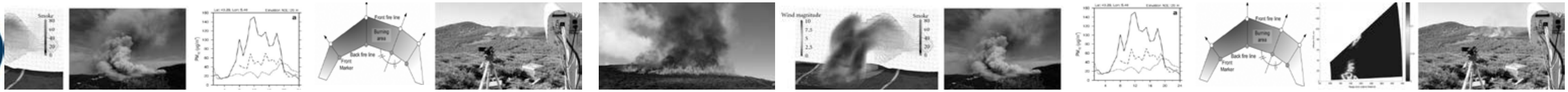
- One of the most **disturbance agent** in terrestrial ecosystems on a global scale (millions of km² per year)

- **Humans** are responsible for about 90% of biomass burning (agriculture, …) especially in tropical and sub-tropical ecosystems

- Since the early 80's, biomass burning is recognized to **emit large amounts of air pollutants**: particles, VOC, NOx, NH3, CO (*Seiler and Crutzen*, 1980)

- **Annual carbon emissions** from biomass burning maybe 50% of those from fossil fuel burning.

- **Atmospheric CO_2 growth rate** interrannual variation maybe strongly linked to interannual variability in fire activity.



From fires to chemical emission: the “bottom-up” approaches

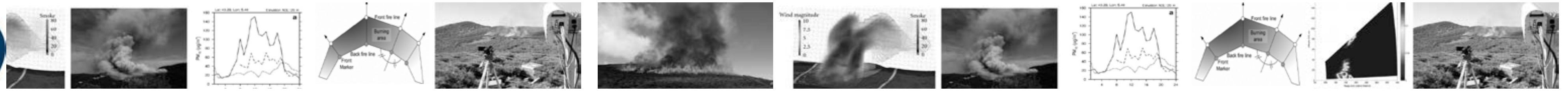
Emission of species i =

1 / *Seiler* and *Crutzen* (1980)

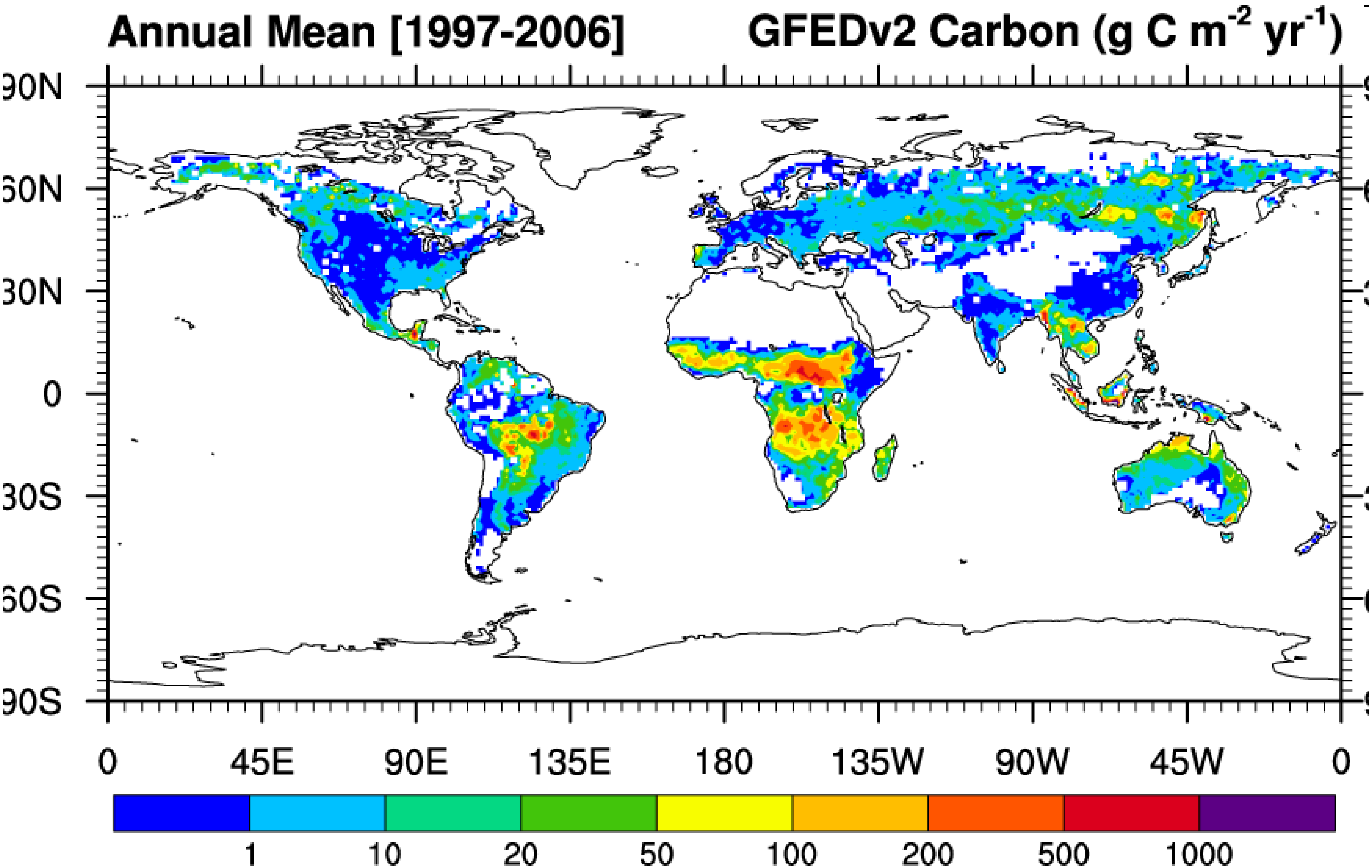
Area burned	x	Fuel load	x	Burning efficiency	x	Emission factor
m2		kg (biomass)/m2		kg(burnt fuel) / kg(available fuel)		kg(species i) /kg(biomass)

2 / *Wooster et* al. (2003/5) (e.g. GFAS

FRE	x	Conversion factor	x	Emission factor
W: Fire Radiative Energy		kg(biomass) / W(FRE)		kg(species i) /kg(biomass)



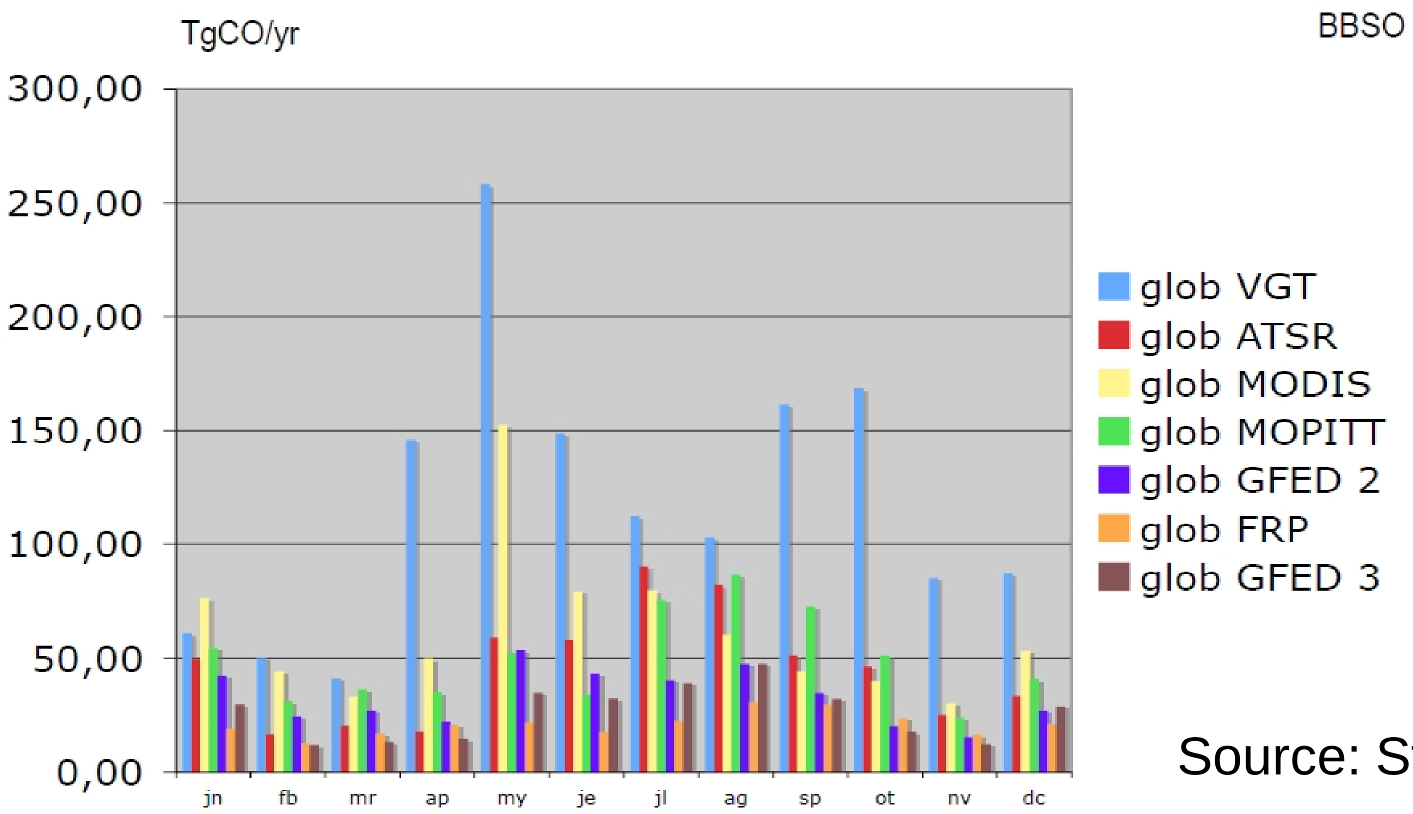
Bottom-up inventory: Global Fire Emission Database



Source: Van der Werf *et al*., 2004

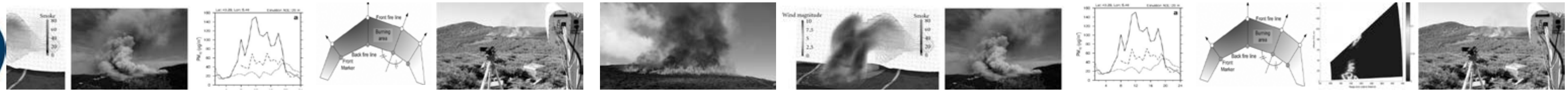
Fires at the global scale:

Comparison of global CO emissions for 2003



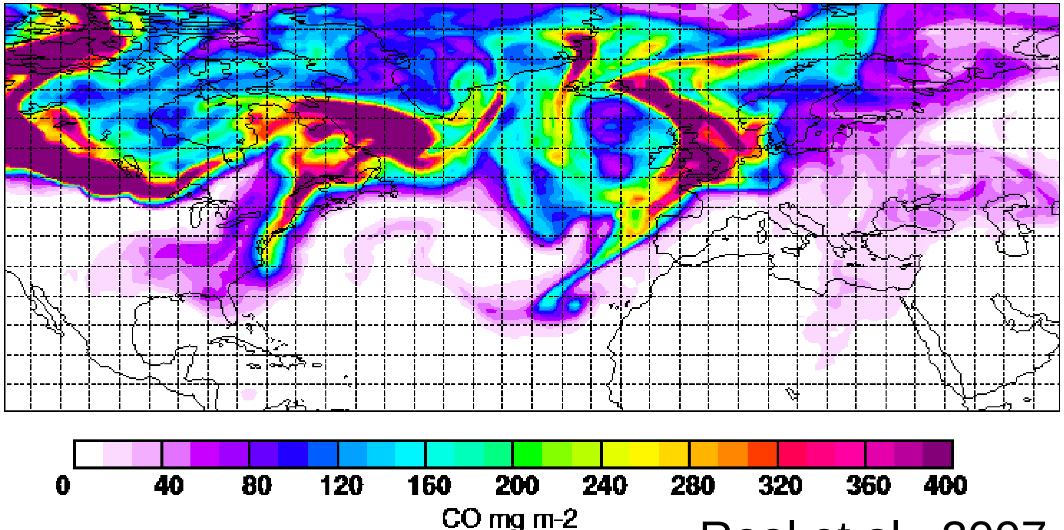
Source: Stroppiana *et al*., 2010

Daunting uncertainties in emissions estimates
→ high variability of fires at scales finer than the resolution of current obs.



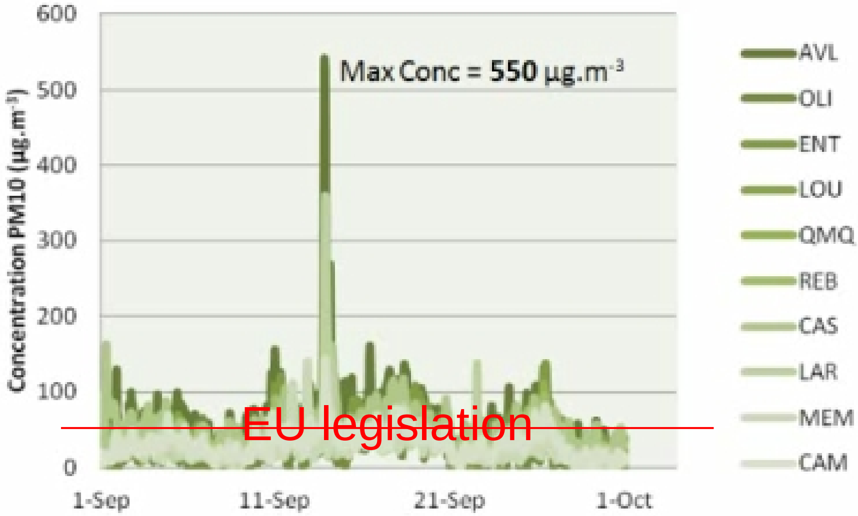
Fires and air pollution

Long range transport of fire plumes modifies background pollution levels



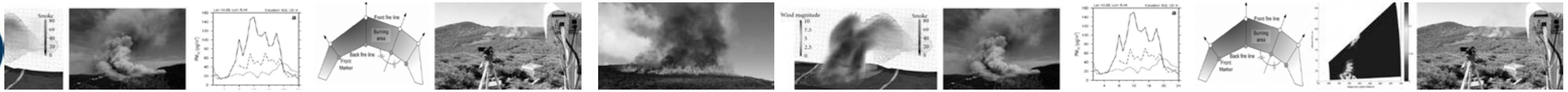
Real et al., 2007

Extreme fire events

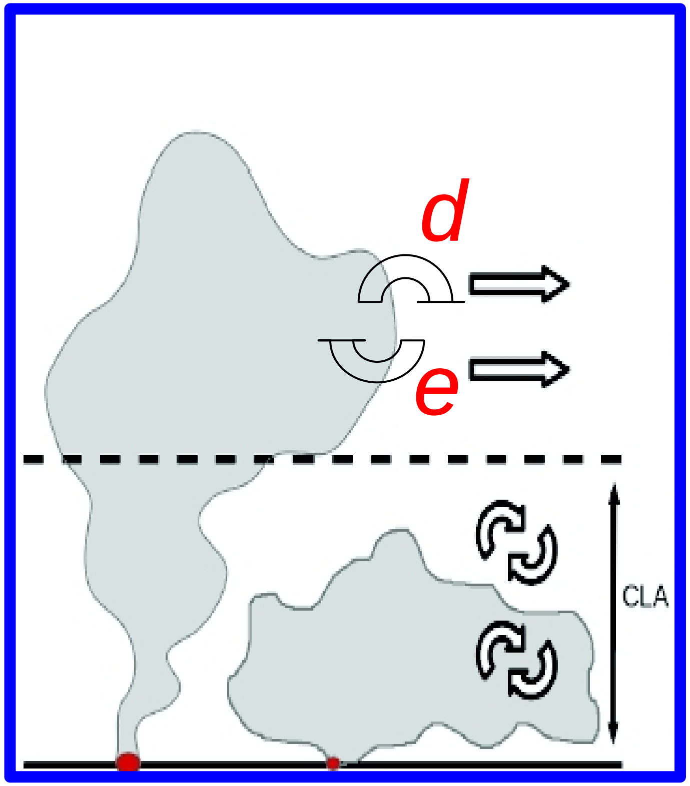


Summer 2003 – Fires in Portugal – Martins et al., 2011

Summer 2010 – Fires in Russia



Injection height: under or above ABL?
a sub-grid scale process



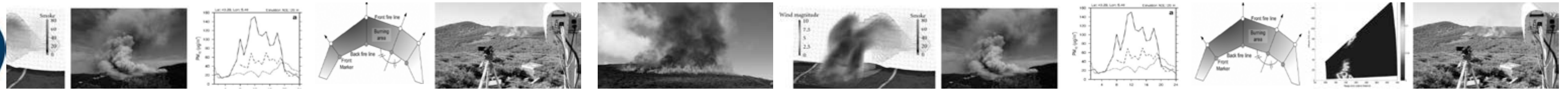
Model Grid cell

- Plume-in-grid models (application to fire ?)

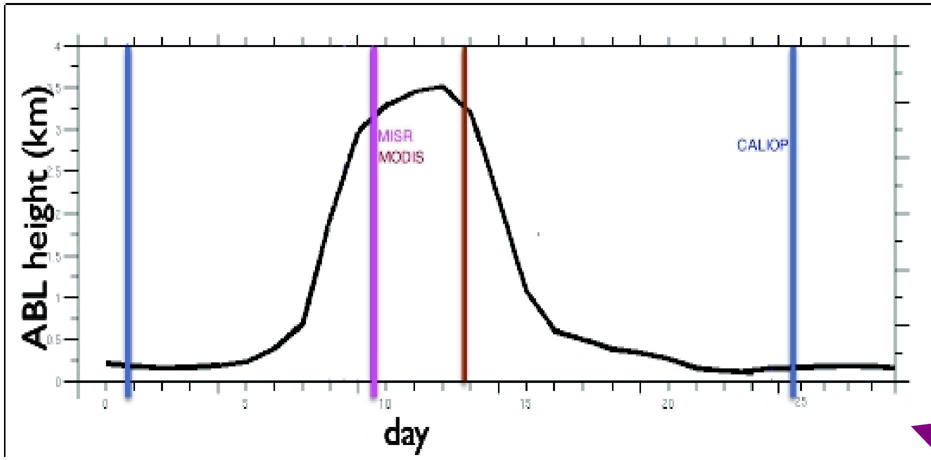
- Statistical models (Sofiev et al., 2012)

- Physical models (1D):

1D PRM model (Freitas et al., 2010)
EDMF (Rio et al., 2010)

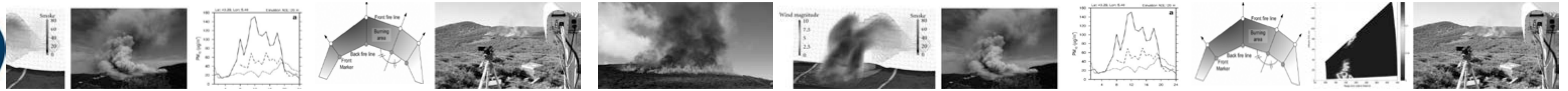


Injection height: under or above ABL?

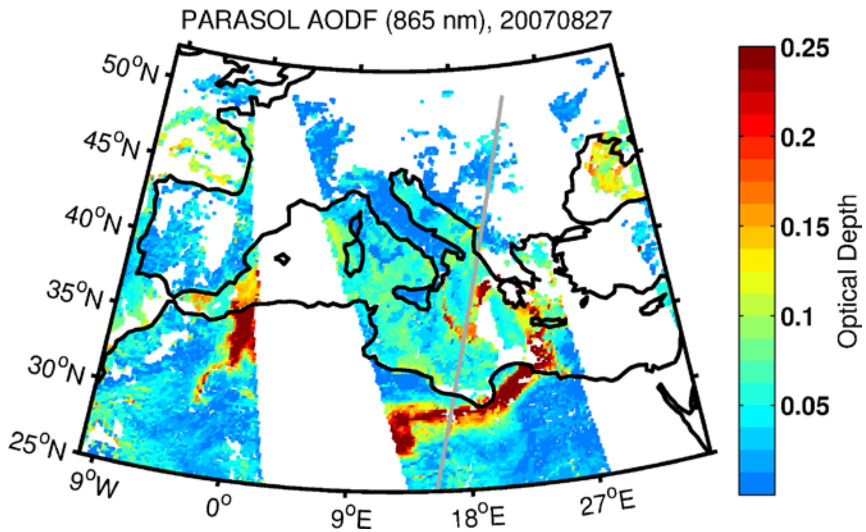


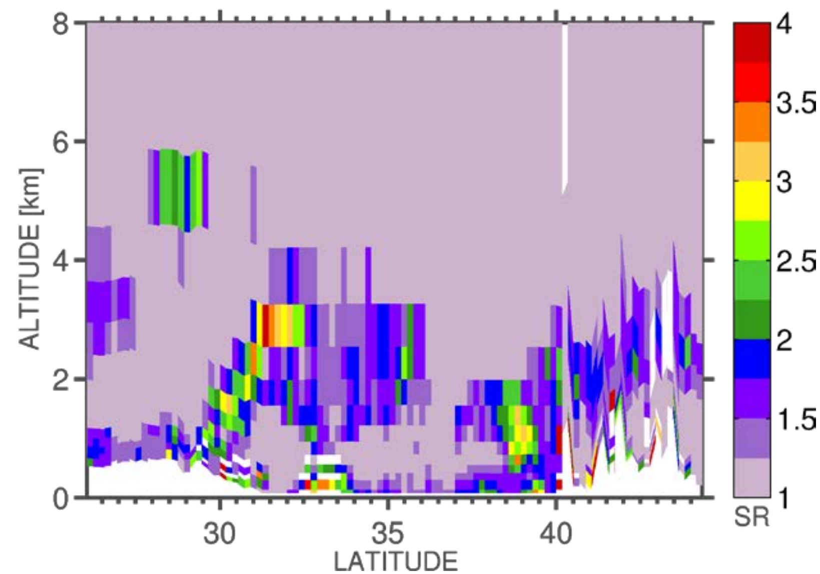
Region	East Europe and Russia	North America	Australia	Euro-Med region
% above ABL (instrument)	48.5% (CALIOP)	4-12% (MISR)	26% (MISR)	9-18% (MISR) 49% (CALIOP) 29% (1D model)
Reference	Amiridis et al., 2010	Val Martin et al., 2010	Mims et al., 2010	This study

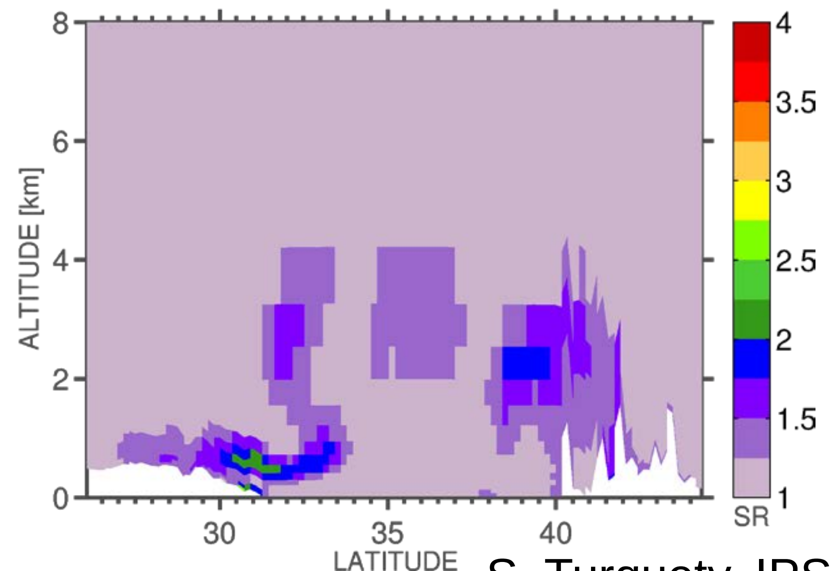
G. Rea, personal communication



Injection height: validation vs. satellite lidar (CALIOP)





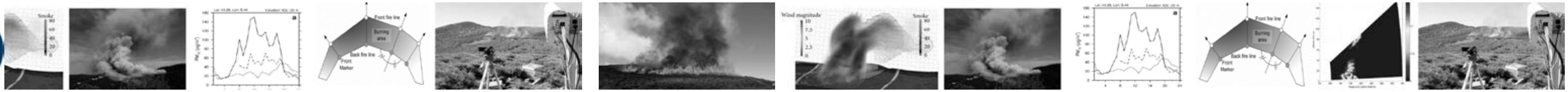


Plume observed 3 times

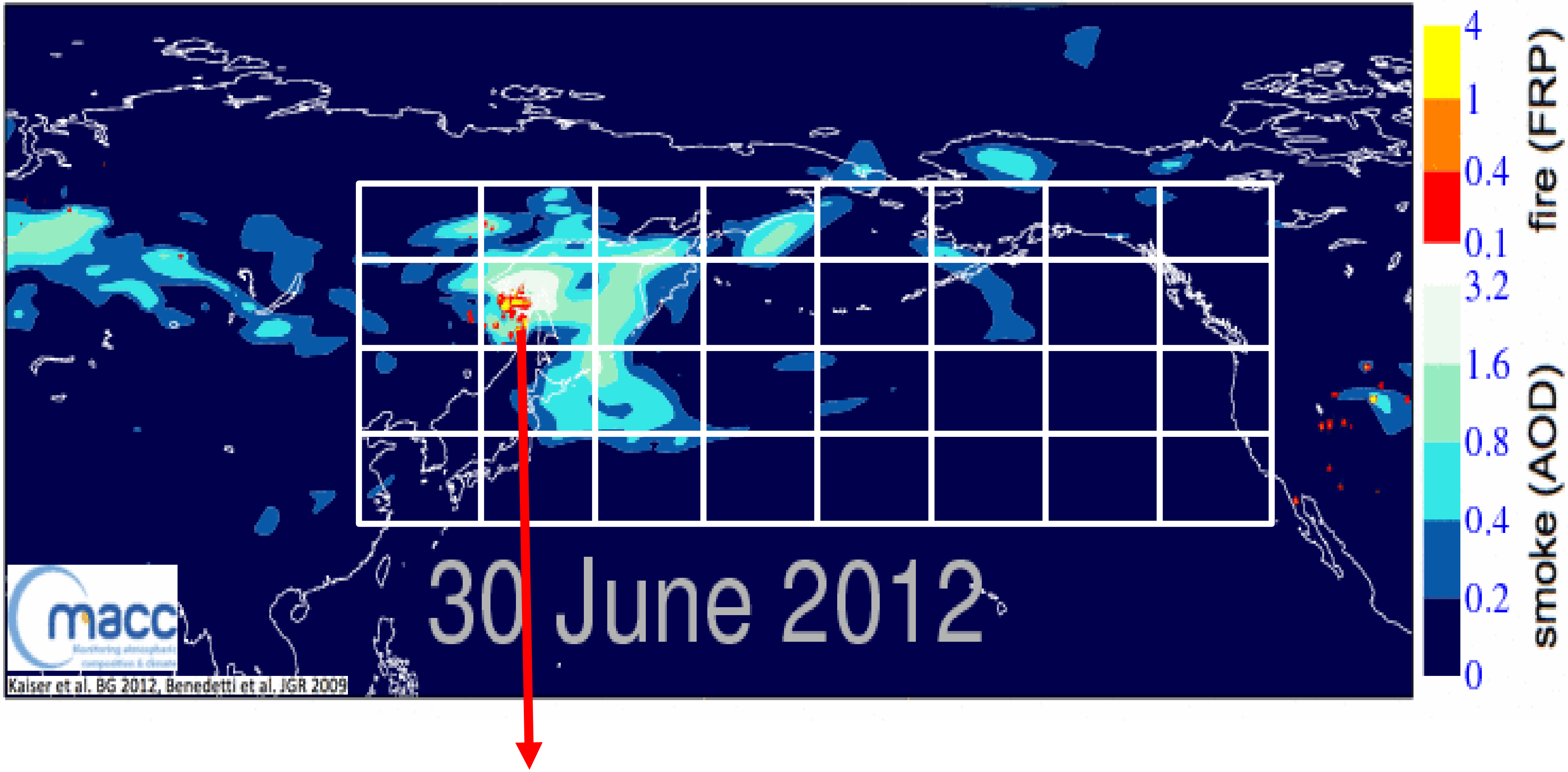
- Main signatures captures
- Under-estimated attenuated scattering ratio R’

- Comparisons indicate too large dilution and dispersion towards high levels

S. Turquety, IPSL, LMD

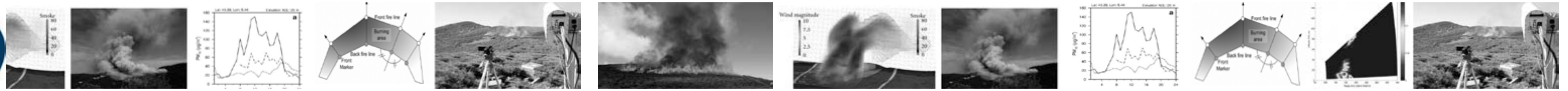


How large is the large scale for fire induced pollution?

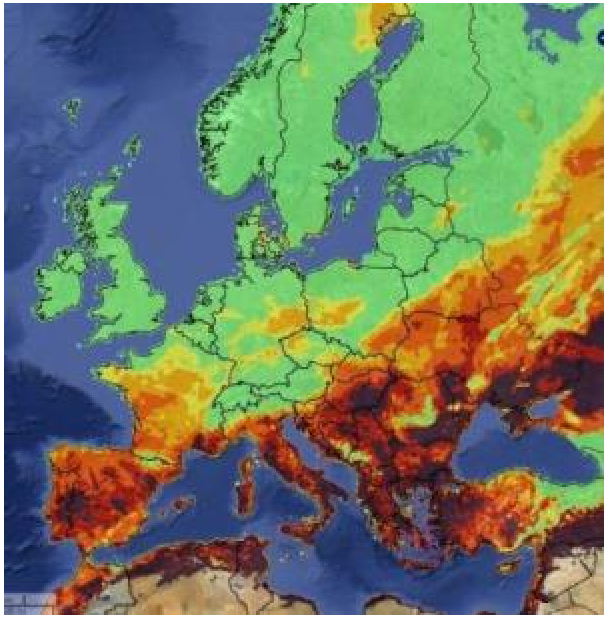


Emissions?
Injection height?
Chemistry close to the source?

Kaiser et al., 2012



Fires in the Euro-Mediterranean region



50000 fires occur in Euro-Med / year

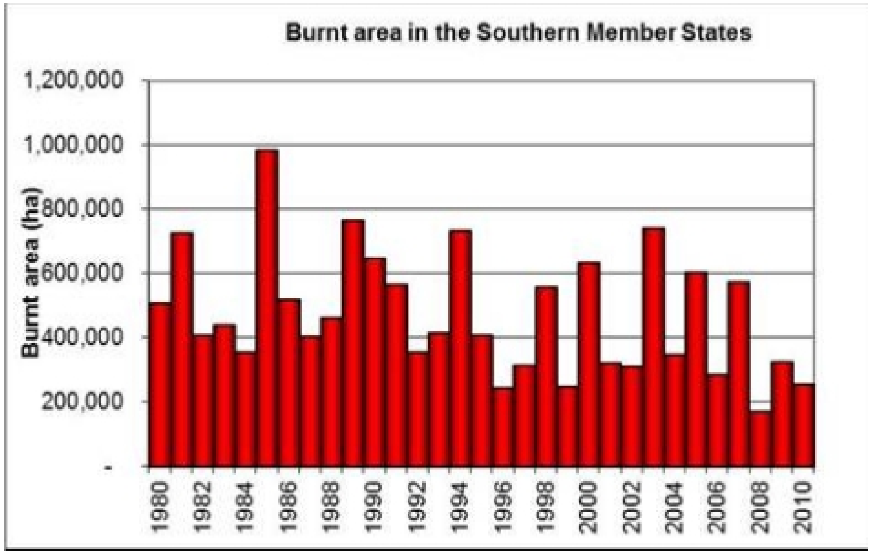
500000 ha of wildland and forest / year

→ 85% of burnt area in the European Mediterranean region (Portugal, Spain, Italy, Greece, southern France)

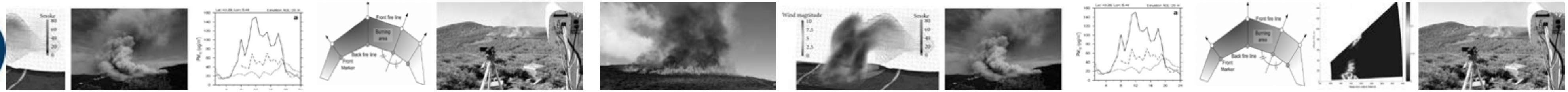
70% occur between June and October (dry and hot summers)

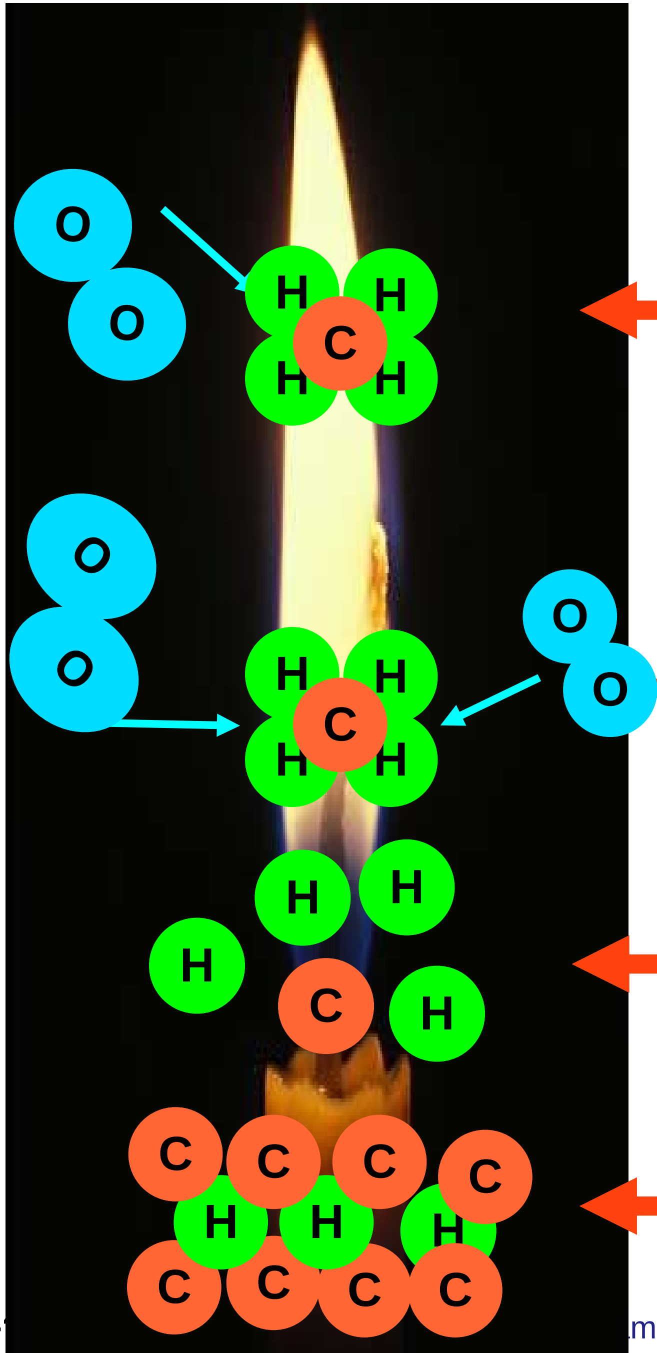
Burnt area decreases → fire prevention strategies / improvement of fire detection → relatively small fires

95% are human induced (traditional agricultural practices, accidental, arson)
→ wildland-urban interface fires



EFFIS report 2011





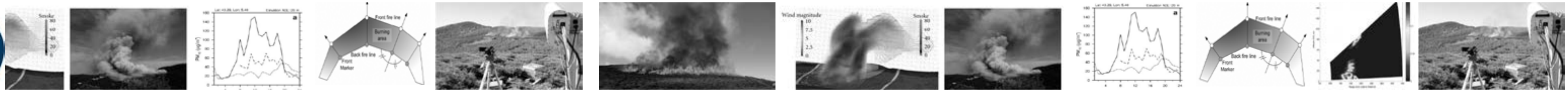
Fires at the flame scale

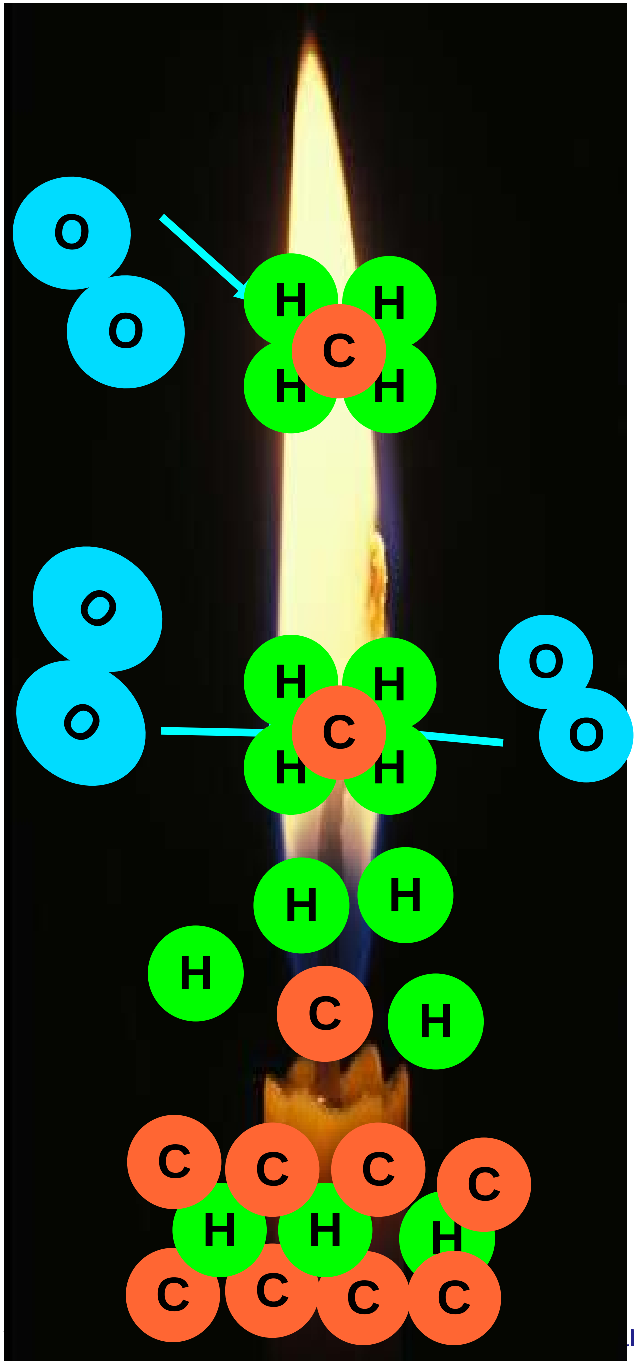
NOT ENOUGH O_2 ?
INCOMPLETE OXIDATION:
$2\ CH_4 + 3\ O_2 \rightarrow 2\ CO + 4\ H_2O$ + **HEAT**

COMPLETE OXIDATION:
$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ + **HEAT**

PYROLYSIS: when fuel turns to gas

Fuel heated





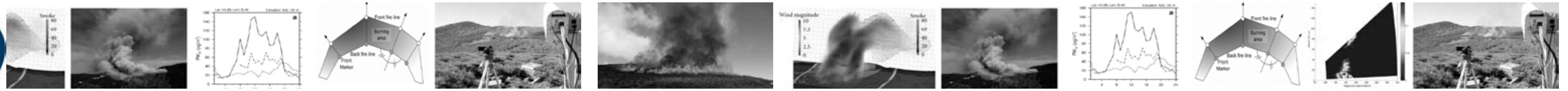
Fires at the flame scale

NOT ENOUGH O2 ?
INCOMPLETE OXIDATION:
Fuel + Air
→ Carbon + CO + CO2 + Water + Nitrogen + **HEAT**

Soot particles

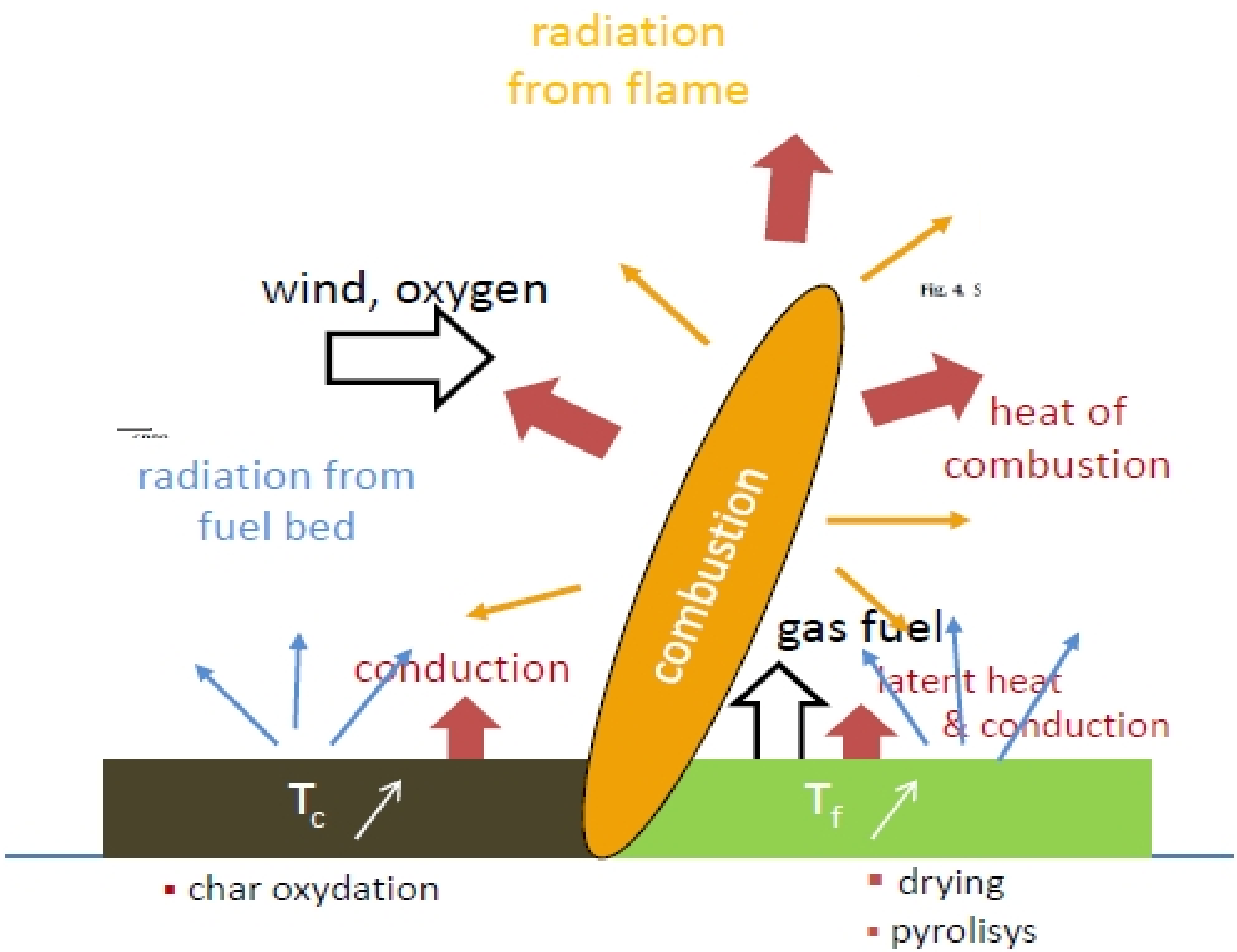
COMPLETE OXIDATION:
Fuel + Air → CO2 + Water + Nitrogen + **HEAT**

PYROLYSIS: when fuel turns to gas

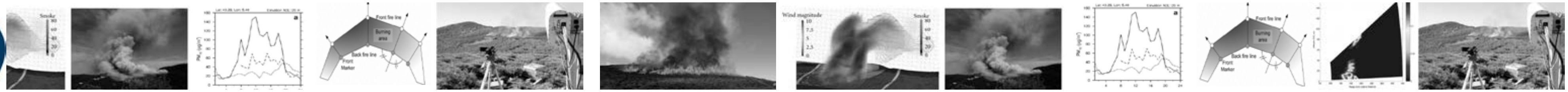


Fire physics – Energy balance

Fire behavior: relation between consumption, radiation and convection



Wooster M., King's College



Fire spread model

ForeFire: Semi-physical fire spread model to calculate the fire rate of spread.

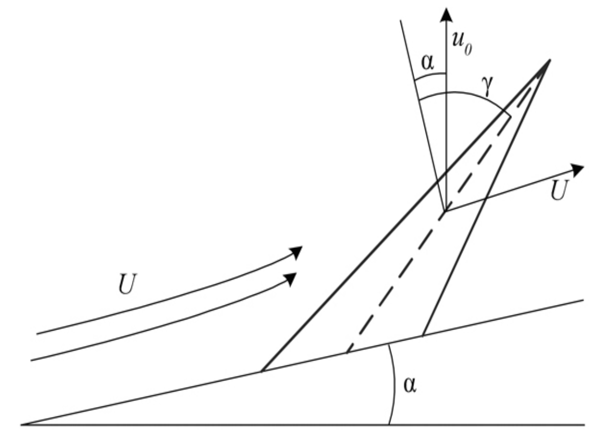
RoS: Analytical formulation where wind and slope effects are explicitly accounted

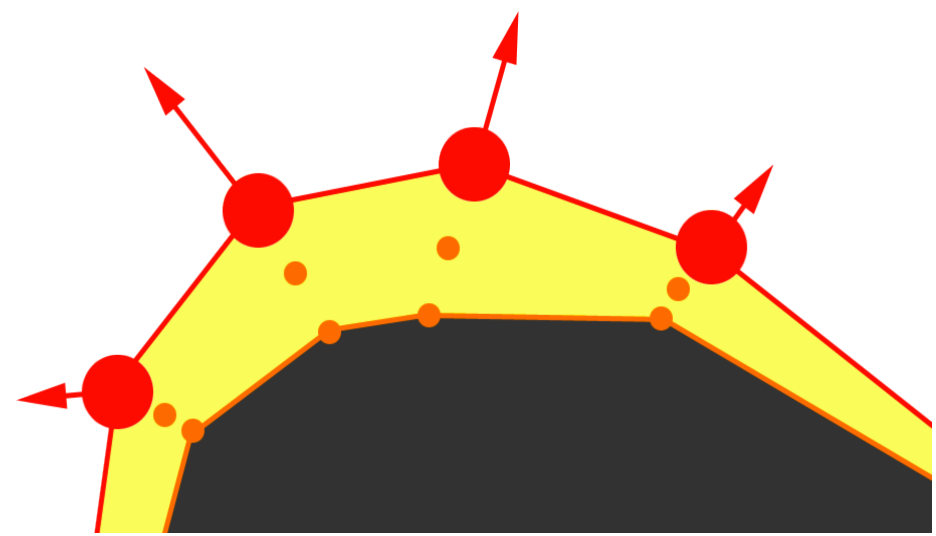
Rothermel's like model: fire behavior is described by the propagation velocity of the fire front

$$R = R_0 + A\frac{R}{1+(R/r_0)\cos\gamma}(1+\sin\gamma-\cos\gamma),$$

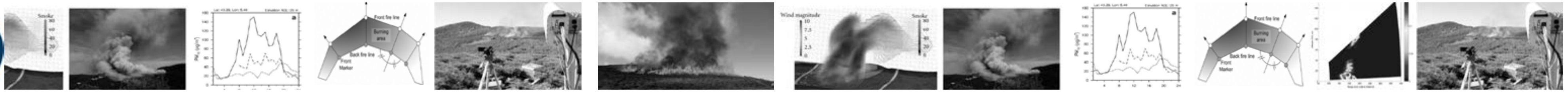
Fire front = tilted radiant panel
which heats the vegetation in front of it
→ pyrolitic step

Advance of the fire front =
front tracking algorithm
(set of markers, fixed burning duration)



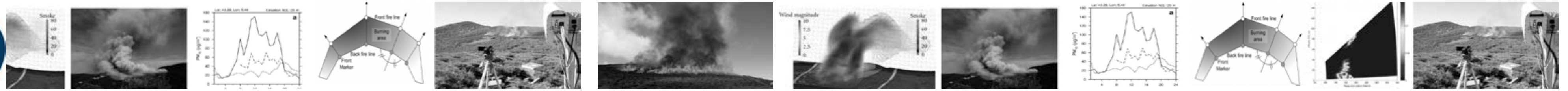


(*Balbi et* al., 2009; *Filippi et* al., 2009)

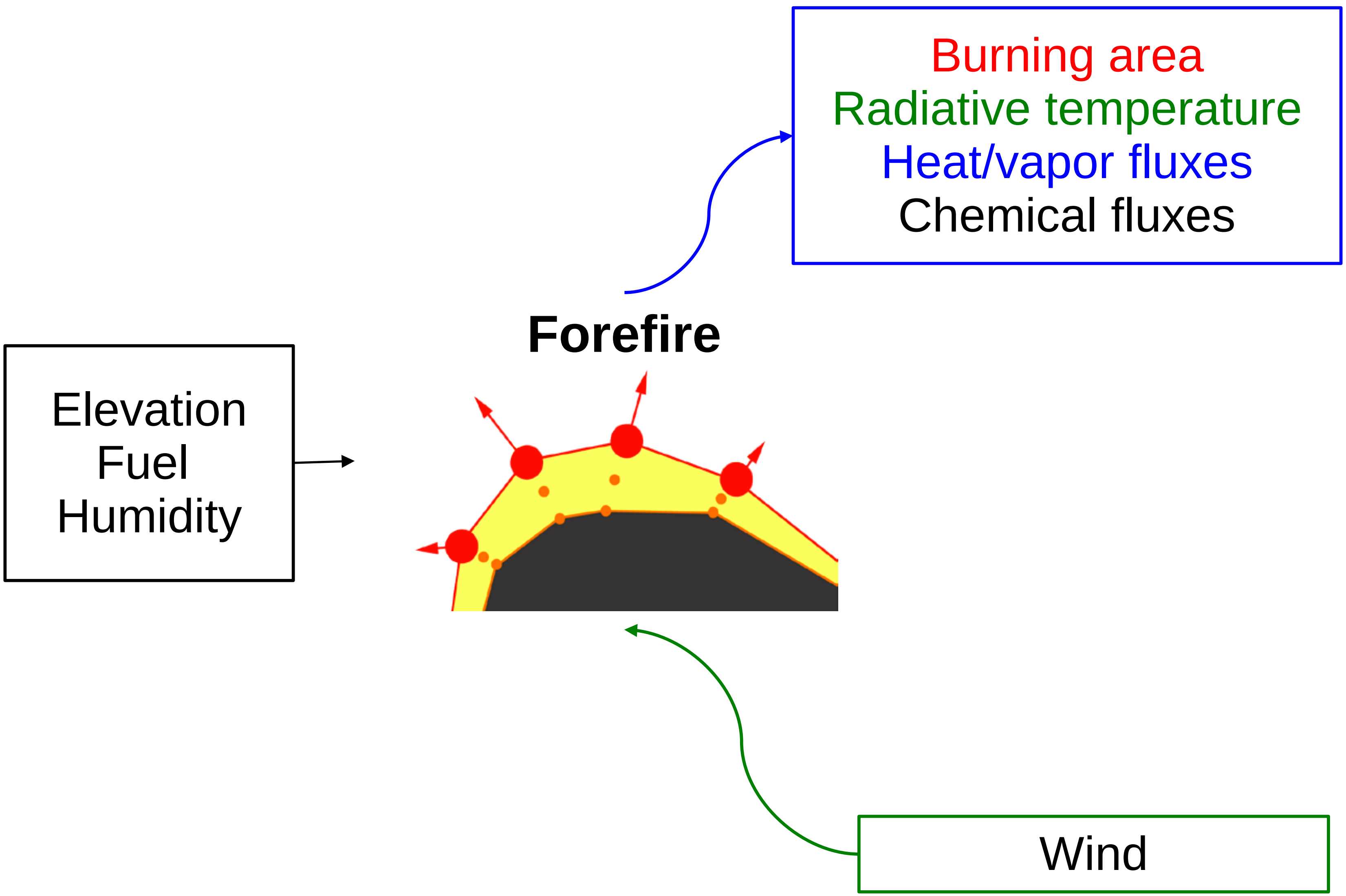


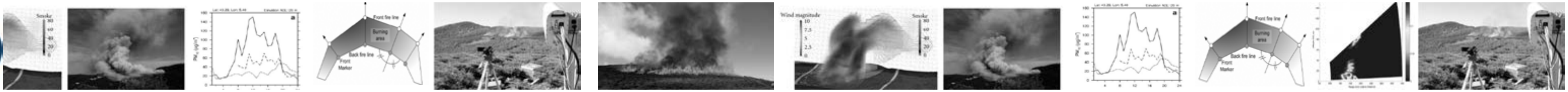
Fire spread model

Try it online : http://forefire.univ-corse.fr



Toward an on-line coupled fire-atmosphere model



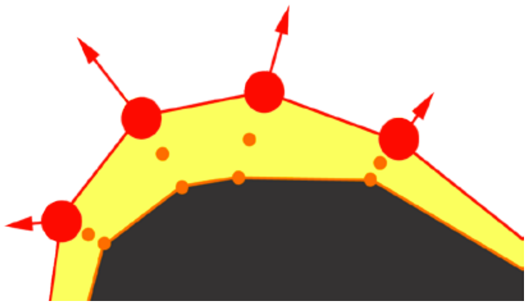


Toward an on-line coupled fire-atmosphere model

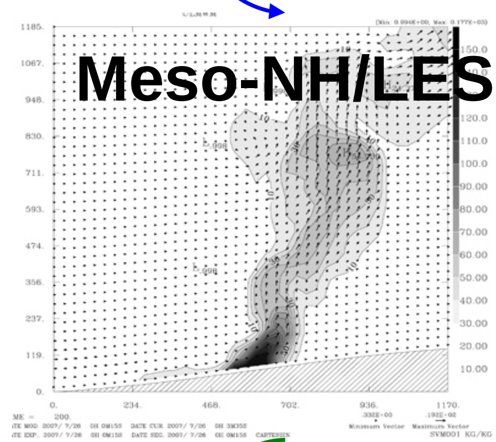
Burning area
Radiative temperature
Heat/vapor fluxes
Chemical fluxes

Elevation
Fuel
Humidity

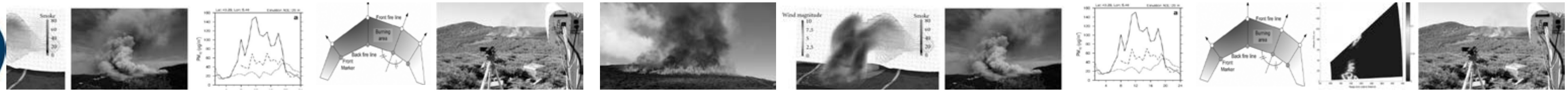
Forefire



Meso-NH/LES



Wind



A mesoscale meteorological model Meso-NH

http://mesonh.aero.obs-mip.fr/

Meso-NH
mesoscale non-hydrostatic model

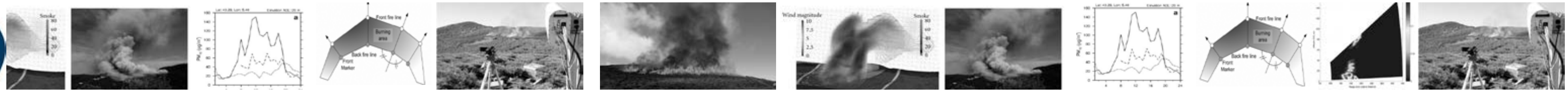
Meso-NH dynamics:

- **Non-hydrostatic**: acceleration of vertical wind – suitable down to metric grid meshes

- The continuity equation contains the **sound waves.**
Pertinent if Mach V/c > 1 but not in meteorology !
→ need to be filtered
→ **anelastic** (removes acoustic waves analytically)
→ uncompressible (mean density varies little)

Meso-NH physics

Part of the model that deal with adiabatic processes, water state changes, subgrid processes, surface interaction, chemistry, **...**

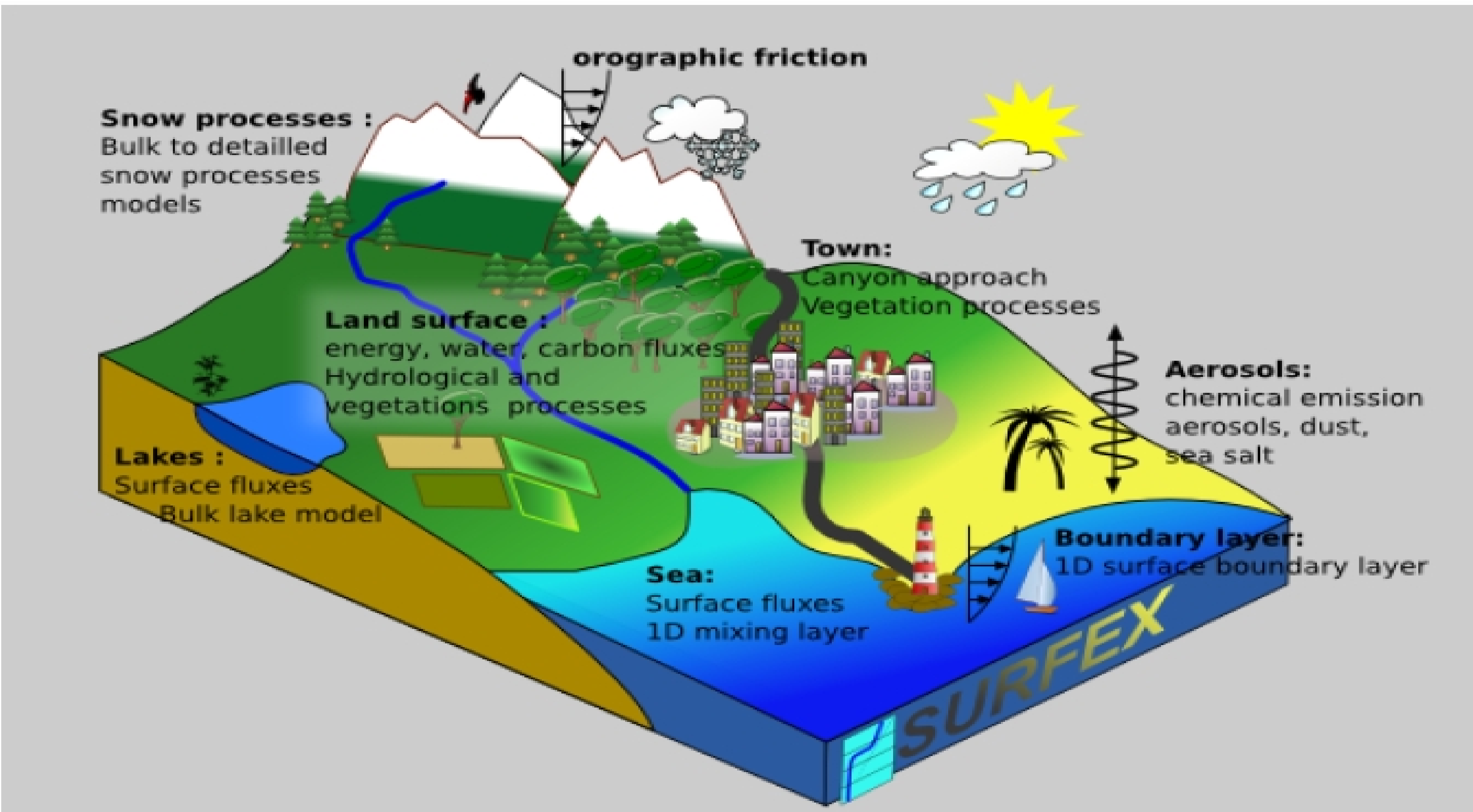


The surface model SURFEX

http://mesonh.aero.obs-mip.fr/

Meso-NH
mesoscale non-hydrostatic model

The surface model SURFEX for representing the ground atmosphere interactions by considering different surface types:

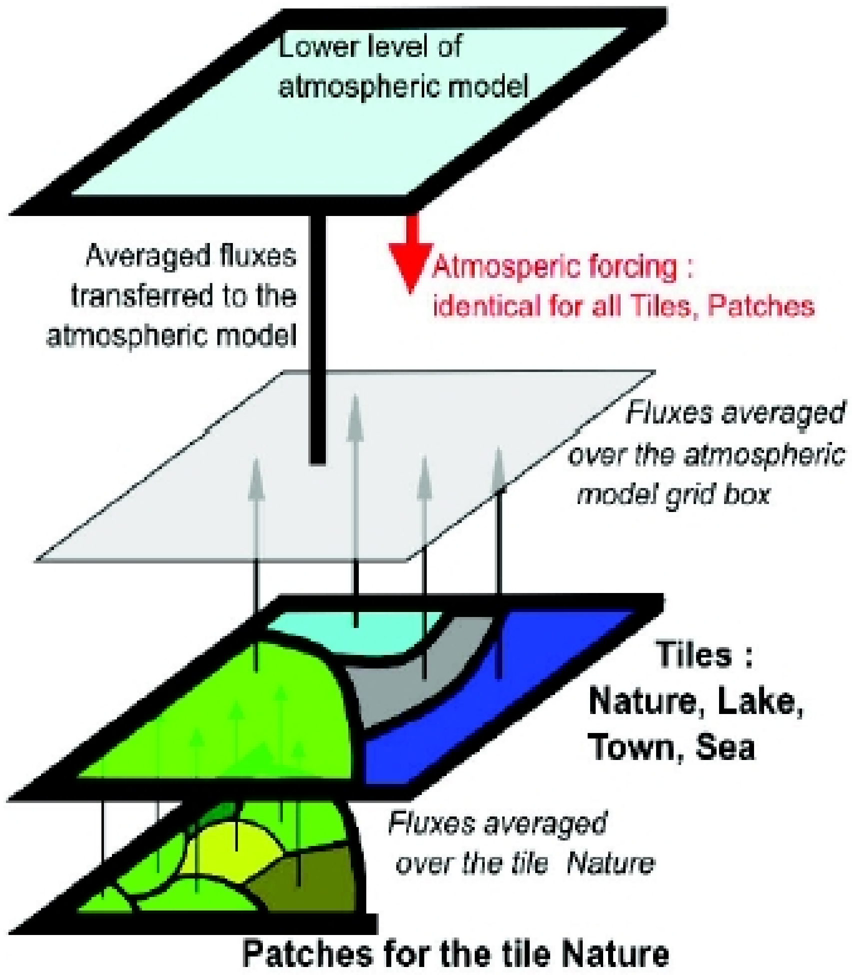


The surface model SURFEX

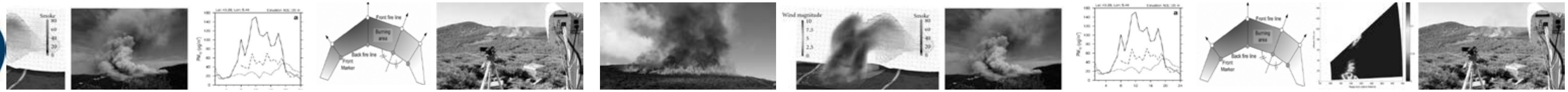
- receives atmospheric forcing

- solves the evolution of the surface

- send back to the atmosphere **the turbulent fluxes: sensible and latent heat fluxes**

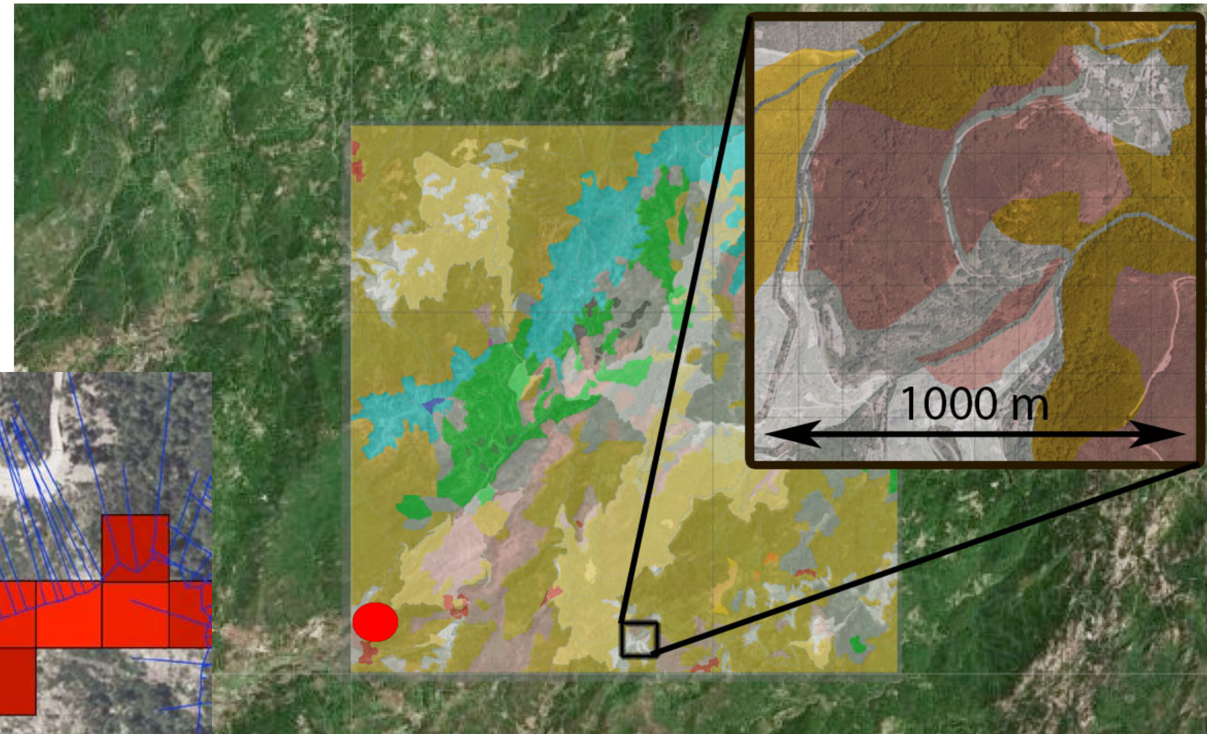


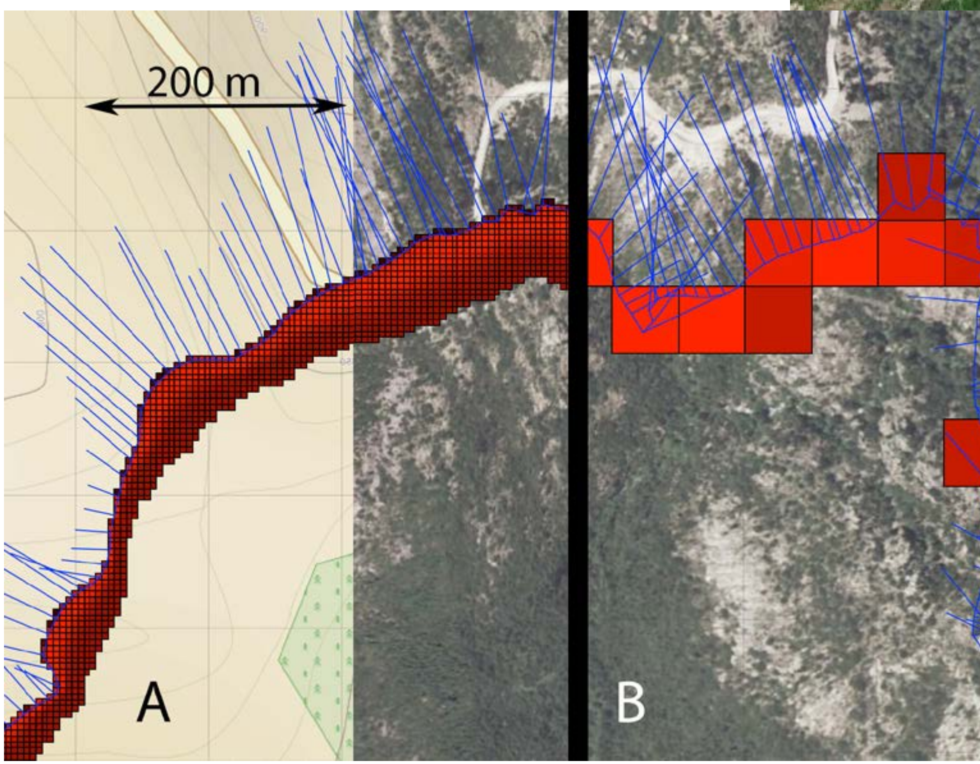
SURFEX tiling and coupling with an atmospheric model



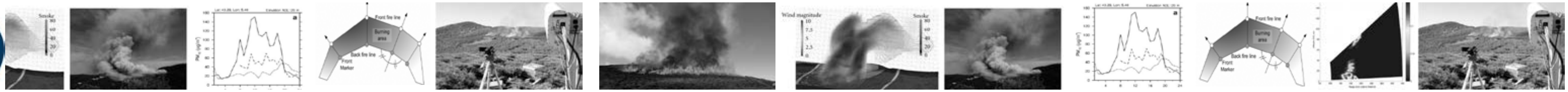
High resolution coupling

Fuel (surface) data : 2 m resolution
(roads, houses)





Sub-grid surface fluxes integration,
combustion fluxes models (5m)
to atmospheric resolution (50m)



Challenges in the fire-atmosphere coupling

Physical impact of the fire into the atmospheric model:

- The model must be able to simulate the fire effects at **high resolution** (10 to 50 m)

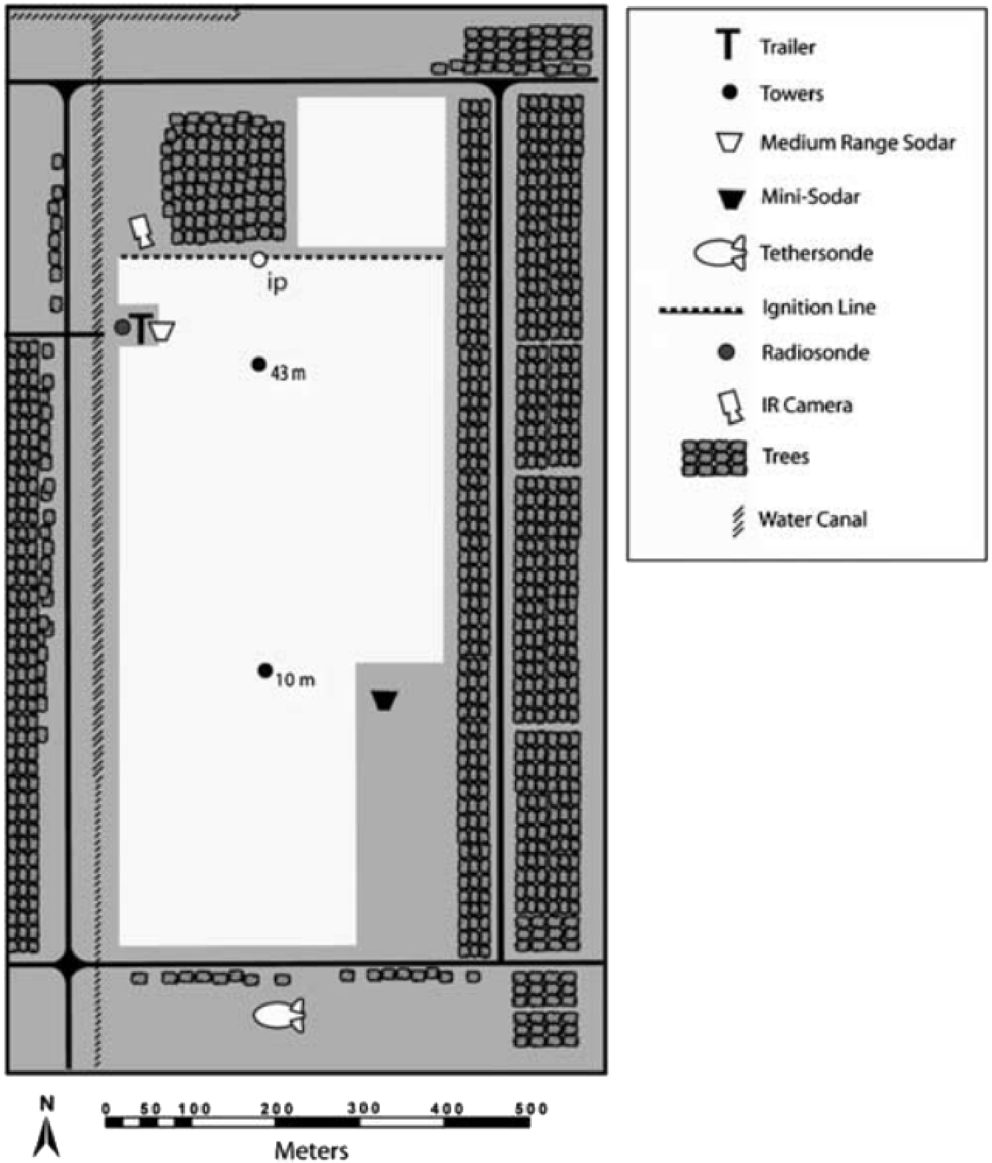
- The upward radiative flux which depends on Ts at the fourth power.
Surface temperature is classically around 300 K. In fires it is ~ 1000 K

→ Upward radiative flux is 100 times larger than usual !!

- The turbulent heat flux:
It usually reaches 200-1000 W/m2.
In fire the heat flux reaches 500 000 to 1 000 000 W/m2

→ Upward sensible heat flux is 1000 times larger than usual !!

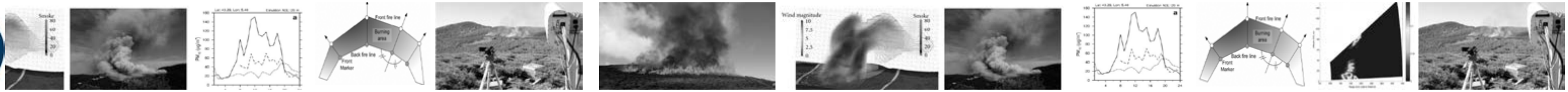
The FireFlux experiment

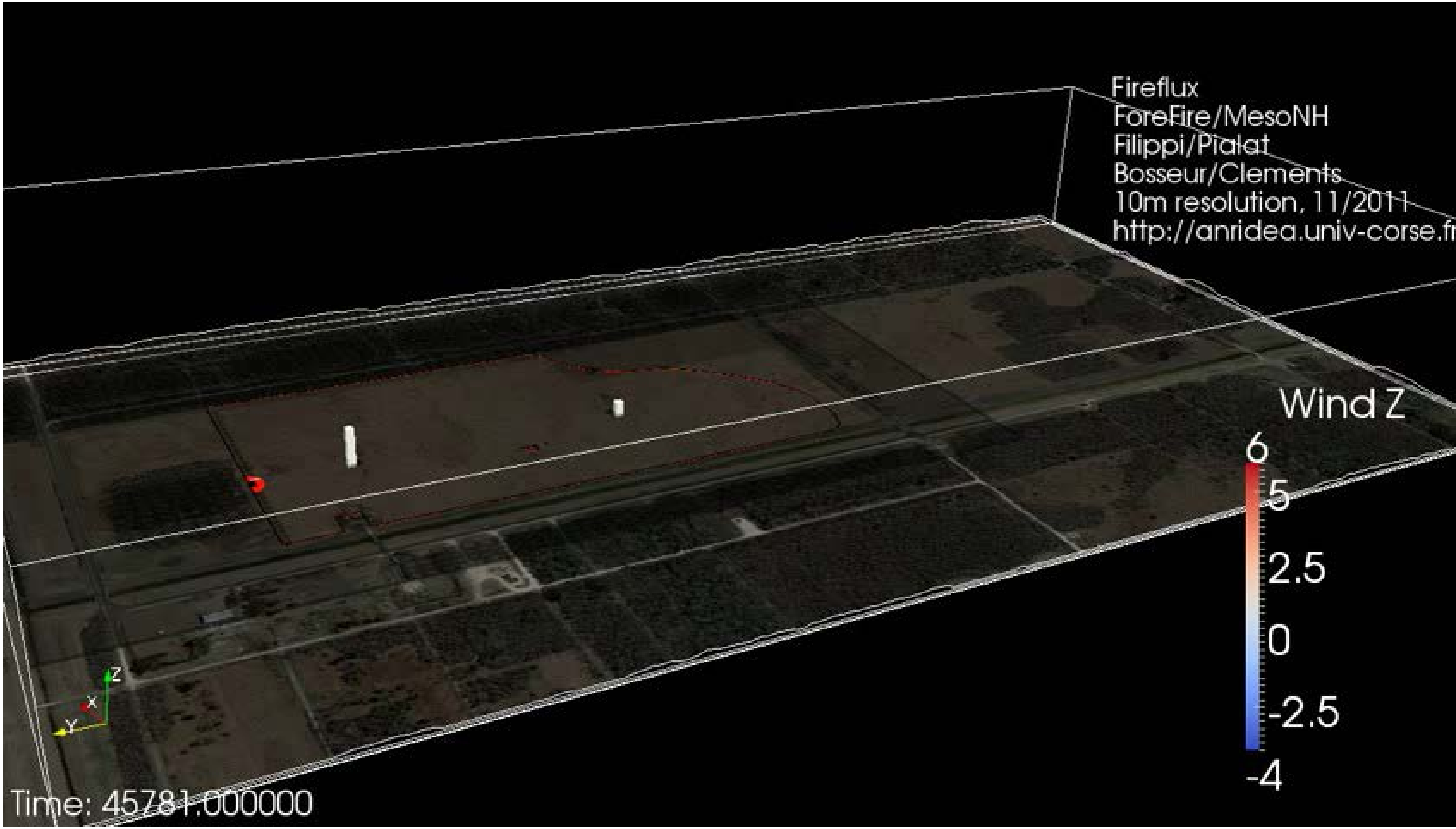


Grass fire

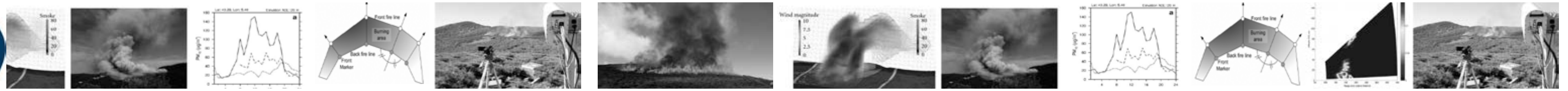
- Experiment by Clements et al,
- 400 by 800 meters
- tall grass (1 meter),
- fuel loading $\sigma = 1.08 kg.m^{-2}$
- flaming duration $\tau = 17s$,
- Ignition temperature $T_i = 505K$,
- lower heating value $\Delta h = 1.543\ 10^7 J.kg^{-1}$,
- fraction of radiant energy $\chi_0 = 0.30$,
- combustion efficiency $E_c = 0.5$,
- total : $\Phi_h^t = 5355 kJ.m^{-2}$,
- nominal heat fluxes about $315 KW.m^{-2}$,
- Dead fuel moisture 9%,
- Burn time = 10 minutes

(*Clements et* al., 2010)

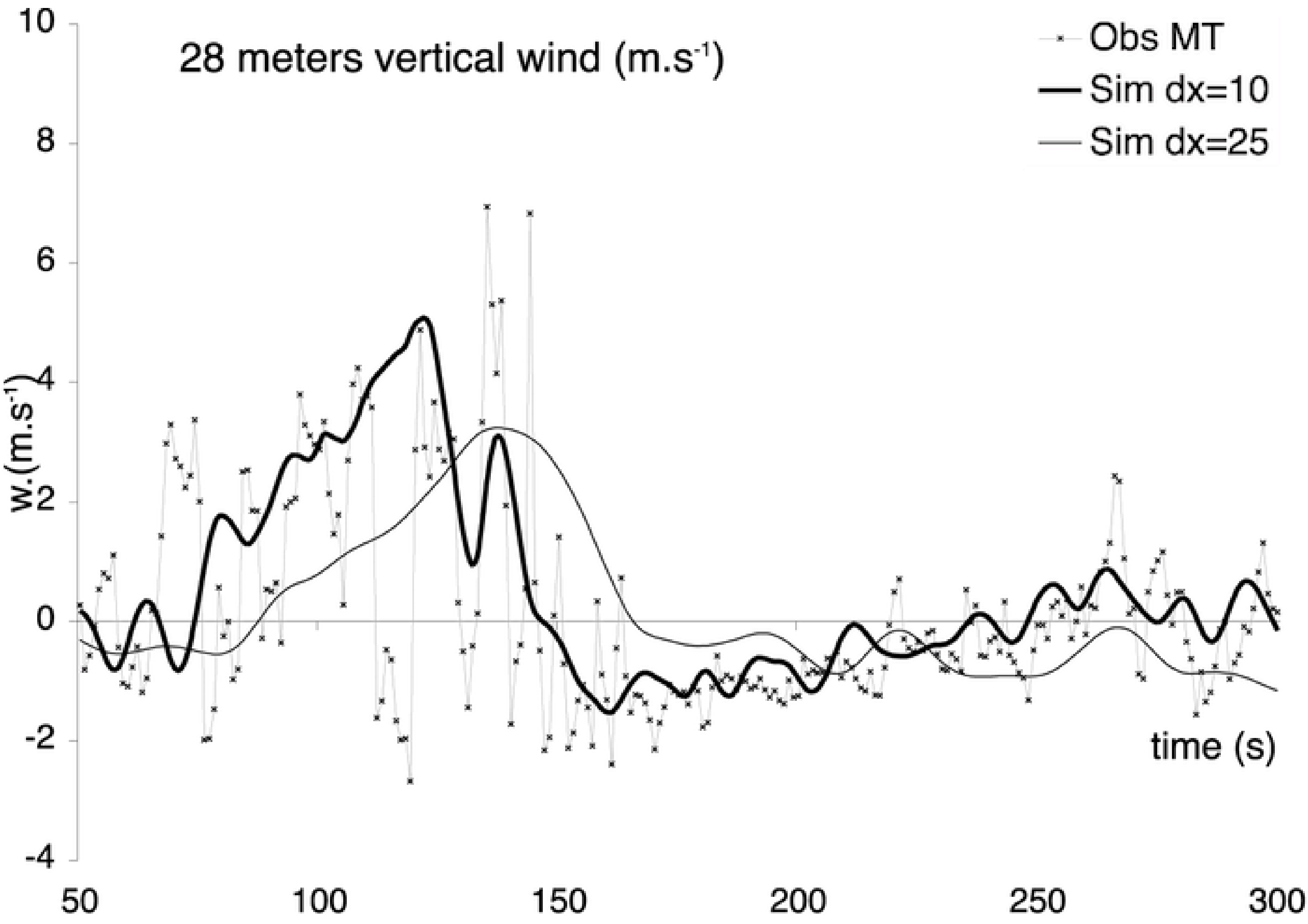




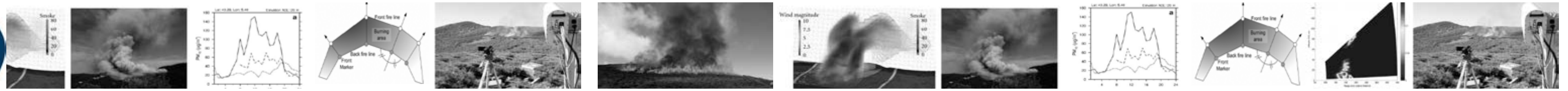
Fortunately, Meso-NH proved able to simulate such extreme conditions without any need to modify the physical algorithms (coupling by fluxes)



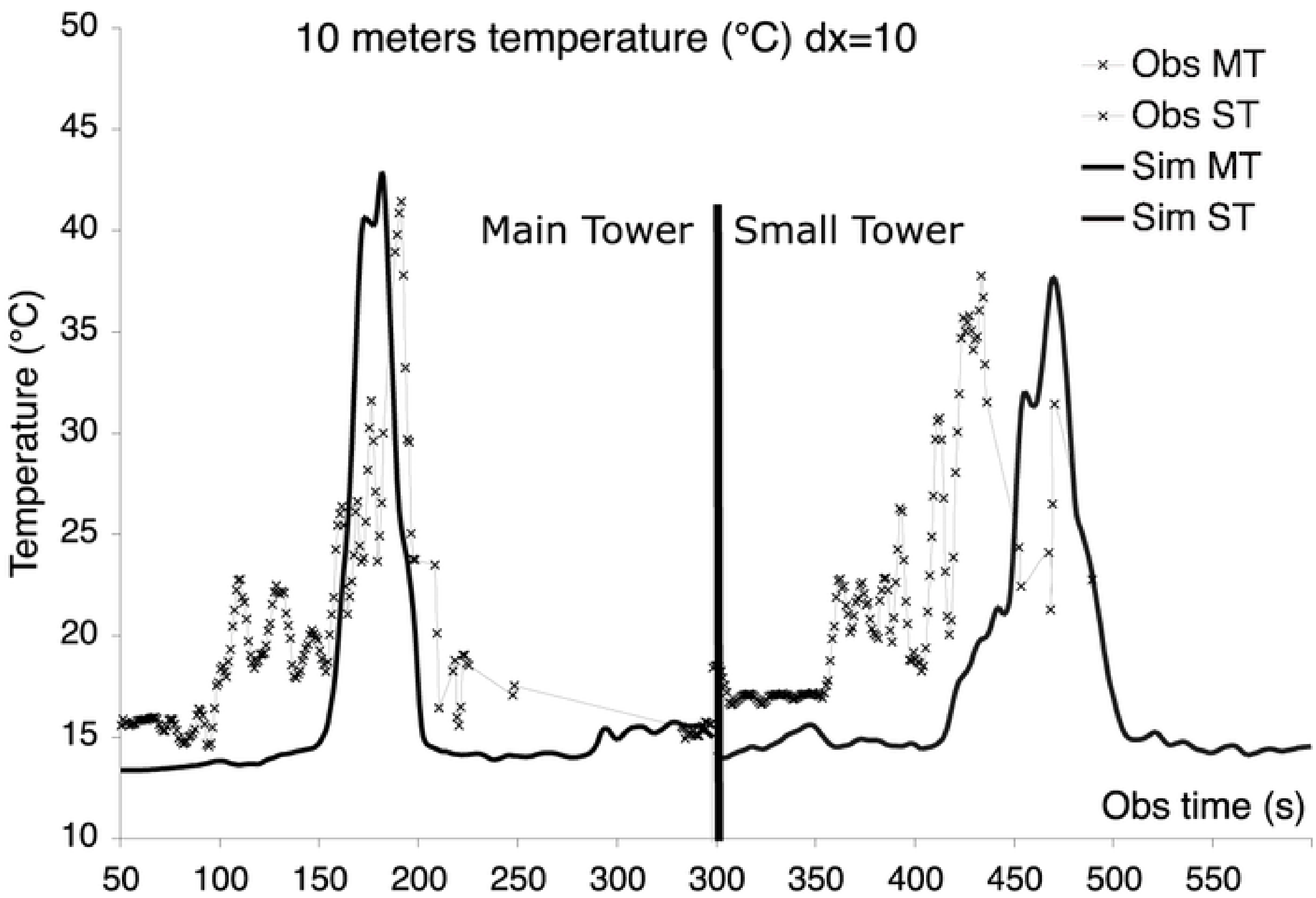
The FireFlux experiment



(*Filippi et* al., 2013)

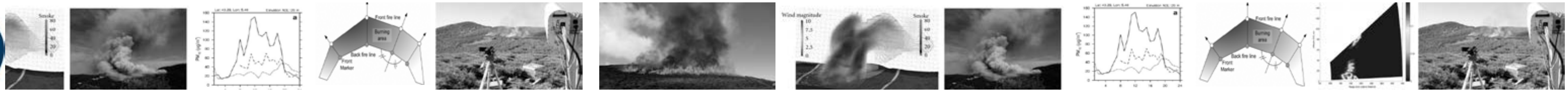


The FireFlux experiment

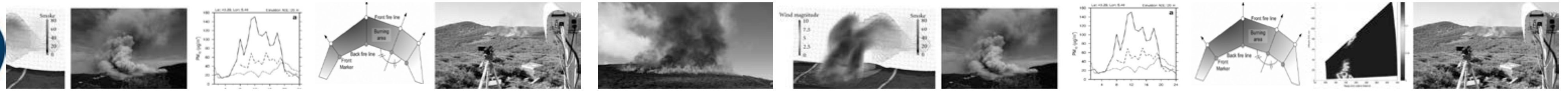


(*Filippi et* al., 2013)

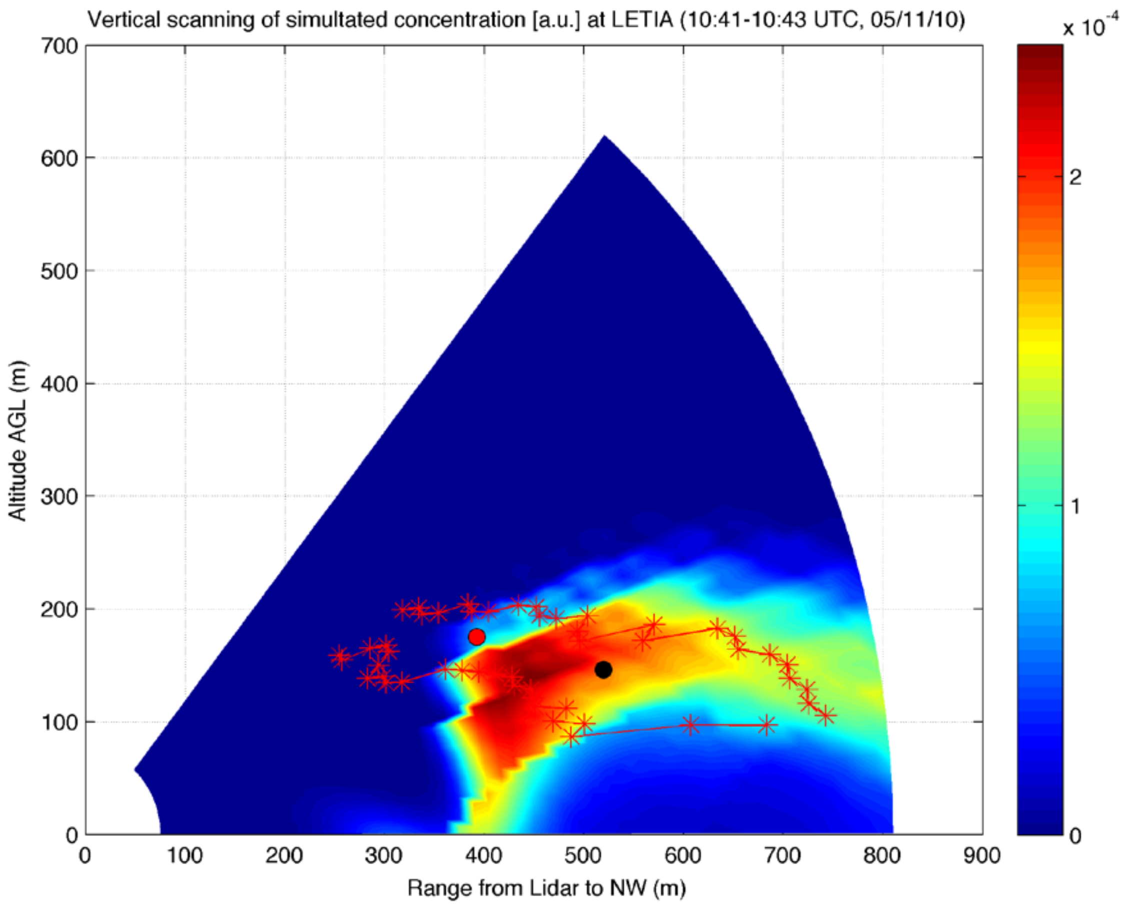
Transport and mixing of smoke plume: the LETIA 2010 experiment (Corsica)



A comparison between lidar and model



A comparison between lidar and model

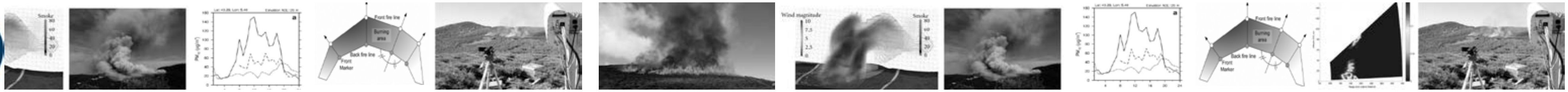


ForeFire/Meso-NH model set-up:

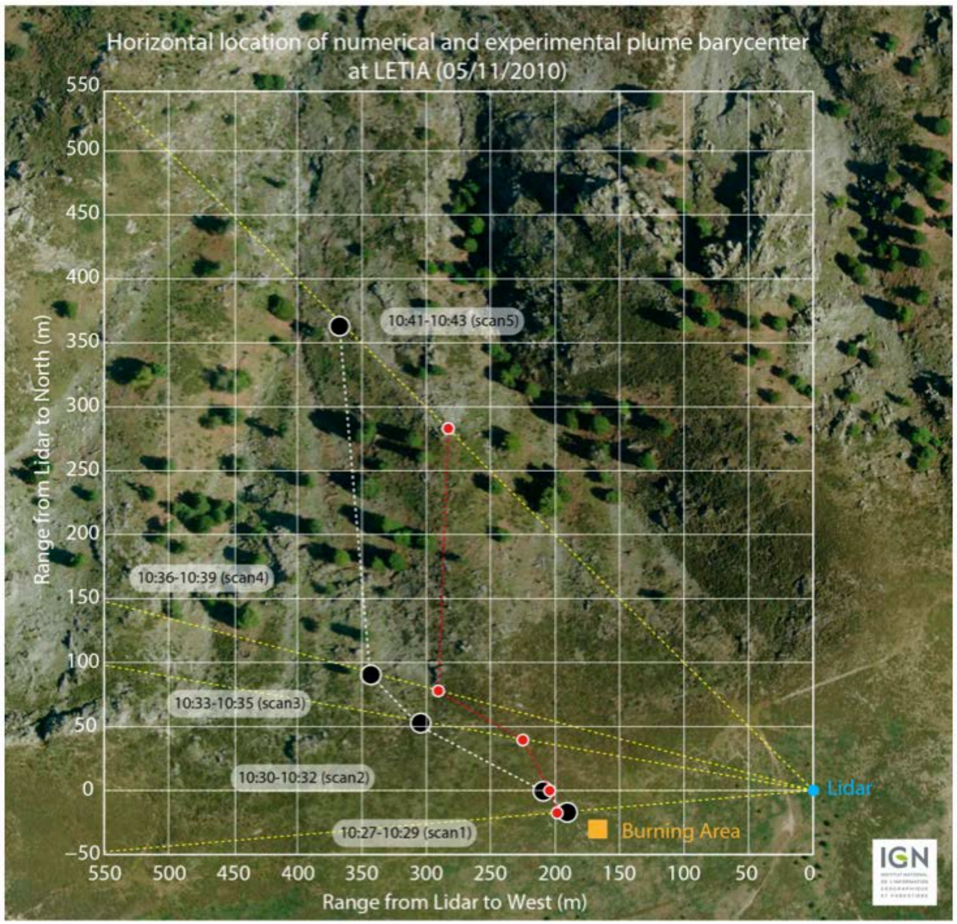
2 nested grids
$\Delta x = \Delta y = 10m$
$\Delta x = \Delta y = 40m$

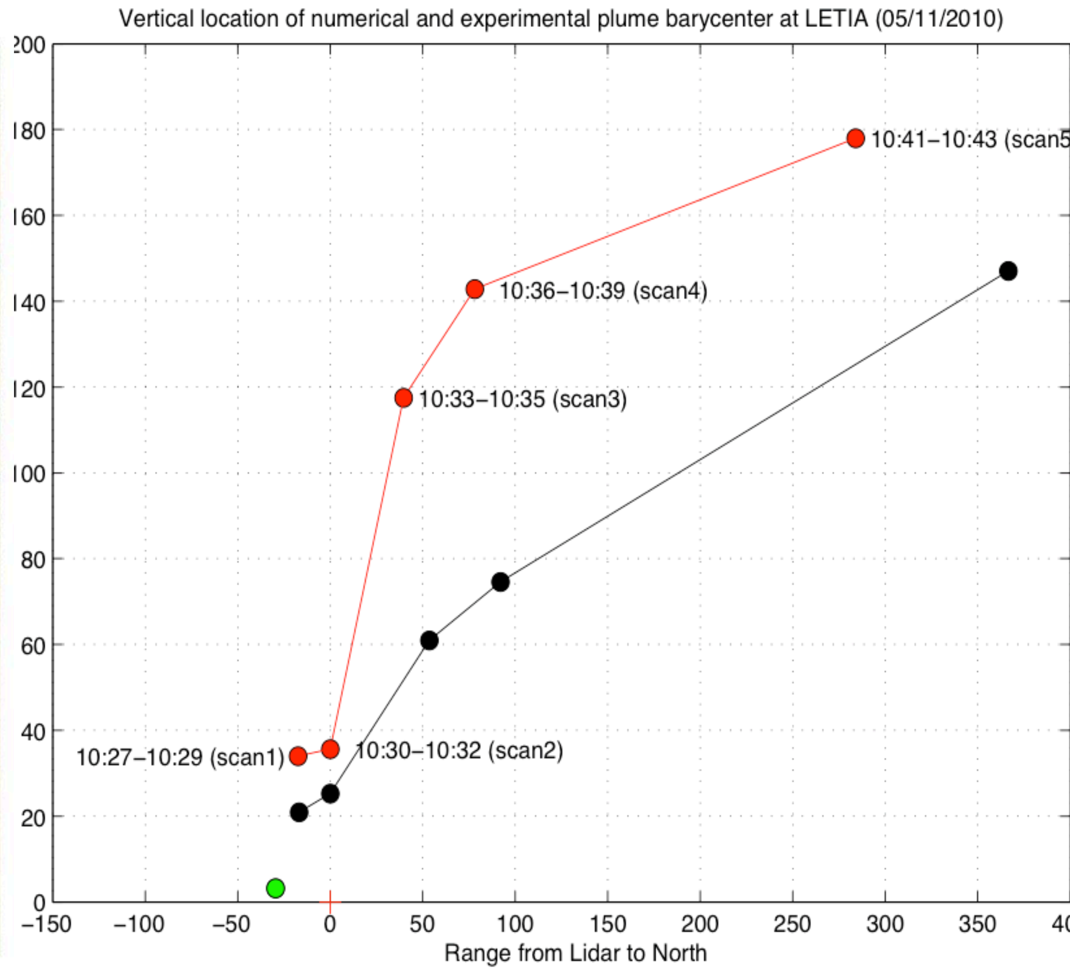
Homogeneous fuel

Heat flux: 155kW/m2



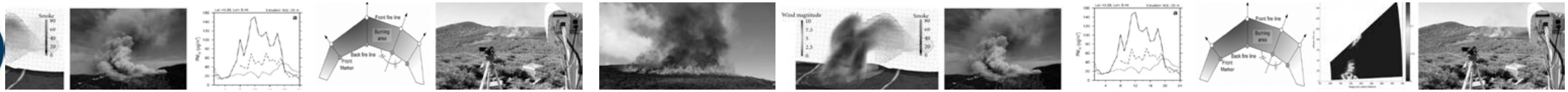
Trajectory and injection height





Cancellieri et al., in NHESS-D 2013

Injection height explicitly resolved (3D turbulence scheme)



Chemical emissions from fires in the Euro-Med region: Emission factors

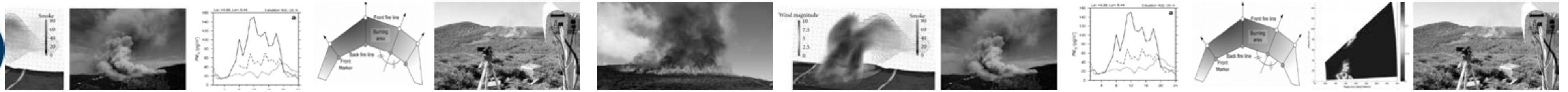
Global estimates for temperate or extratropical forests
(Andreae and Merlet, 2001; *Agaki* et al., 2011)

Mediterranean vegetation type: resinuous, schrubland, eucalyptus, deciduous
No detailed VOCs. *(Miranda et* al., 2004)

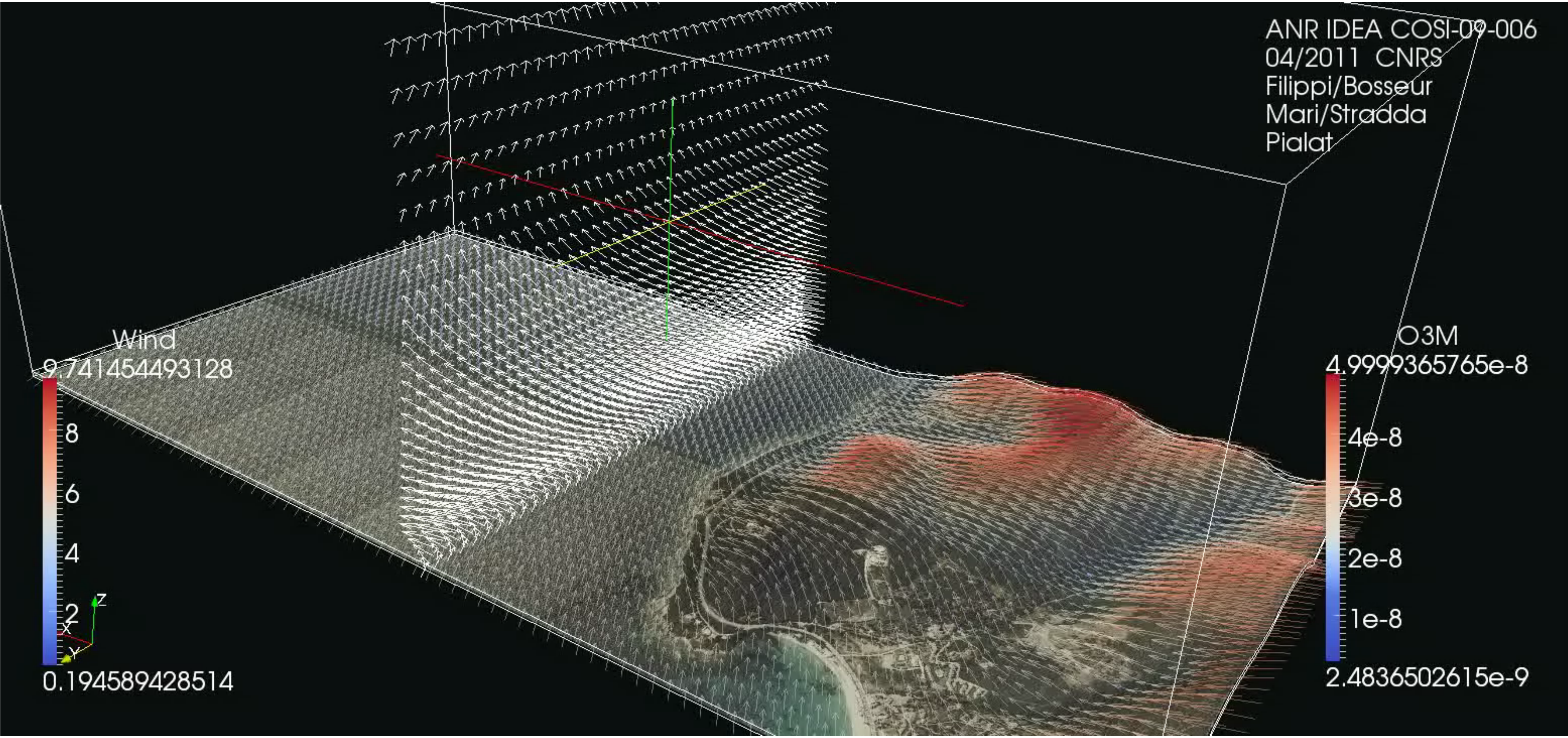
Combustion chamber → strong variation in the CO/CO_2 ratio between kermes oak (<1), rosemary (1), cypress (3), eucalyptus (9).

→ toward emission factors models (fuel composition, structure and burning conditions)

Burning in Corte ! 2012

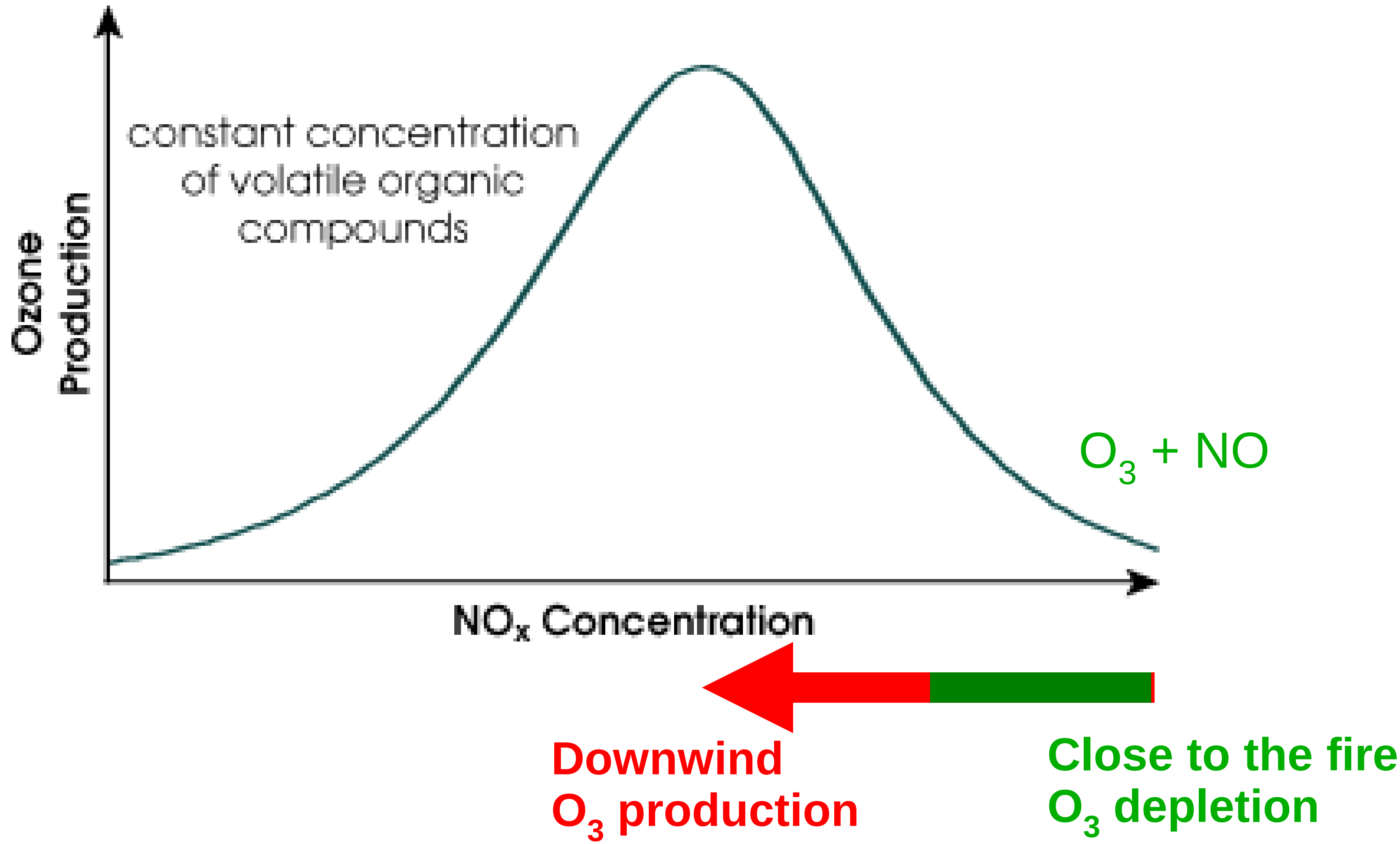


Fire-atmosphere-chemistry coupled simulation

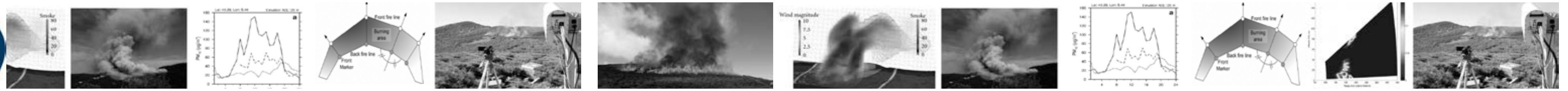


→ high resolution simulation preserves the strong concentrations of NOx in the smoke plume (no instantaneous dilution of NOx in large grid cell) → ozone titration

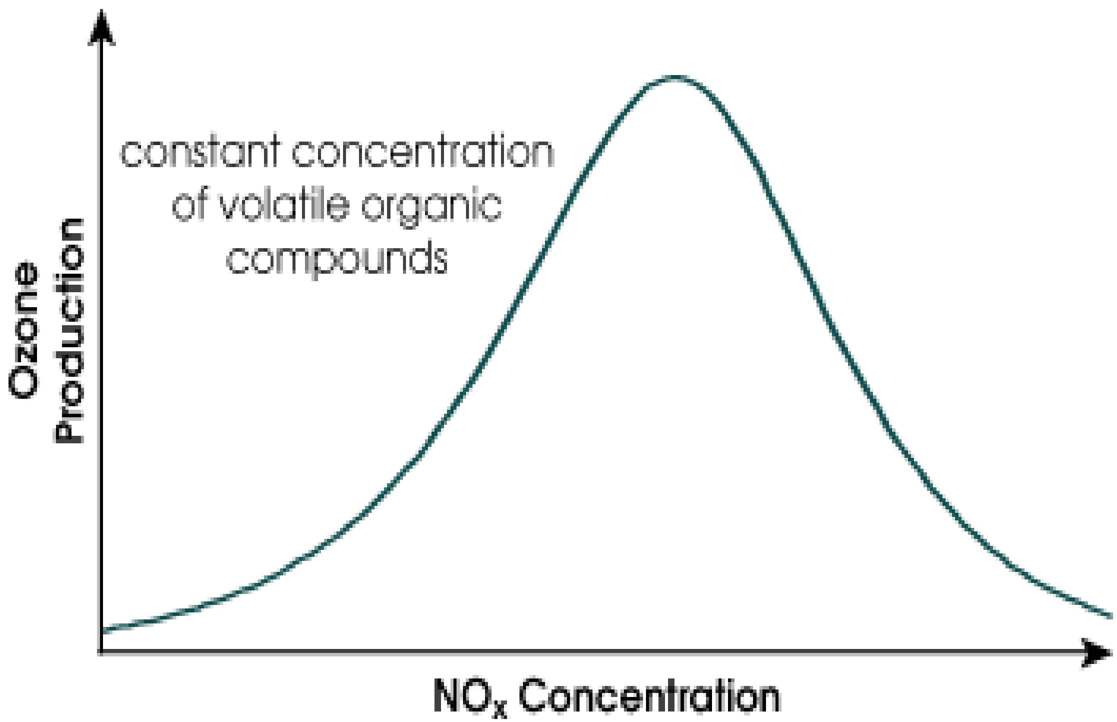
Chemical aging of polluted plumes: the ozone story



Jost et al., 2003; Trentmann et al., 2003; Masson et al., 2006

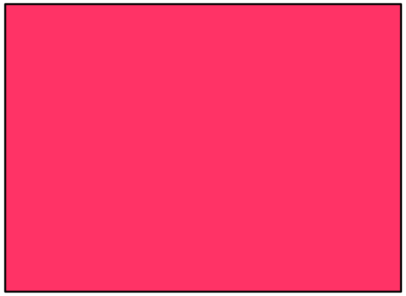


Chemical aging of polluted plumes: subgrid-scale chemistry



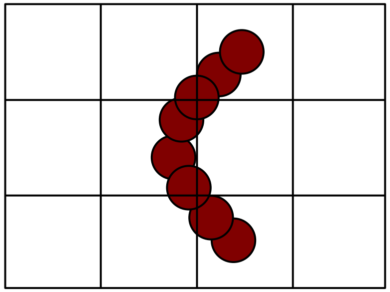
Low resolution models will overestimate ozone production due to concentrated (sub-grid scale) sources !

O3 production

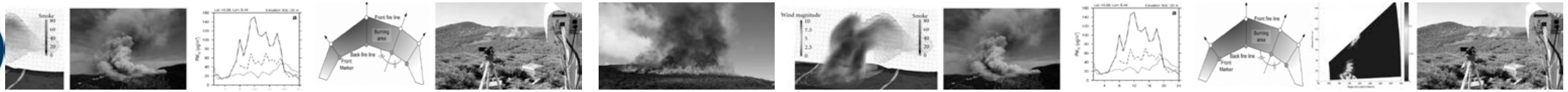


Low resolution

O3 depletion



High resolution

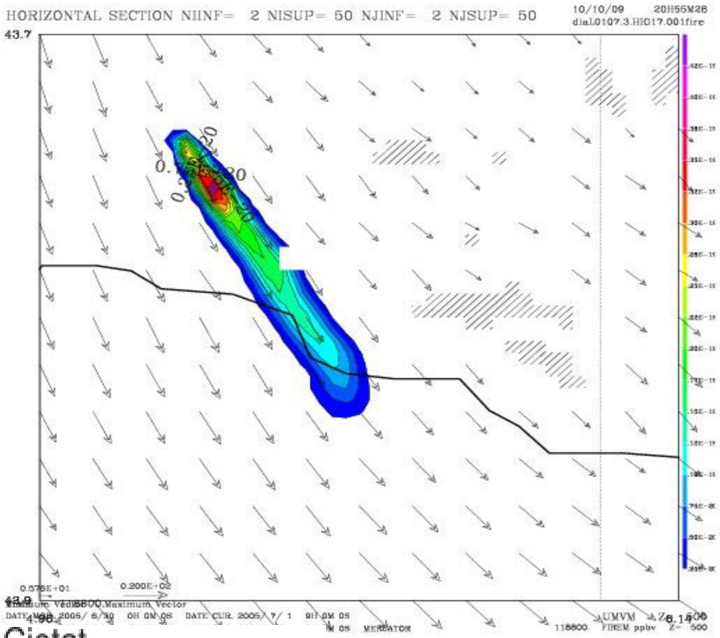


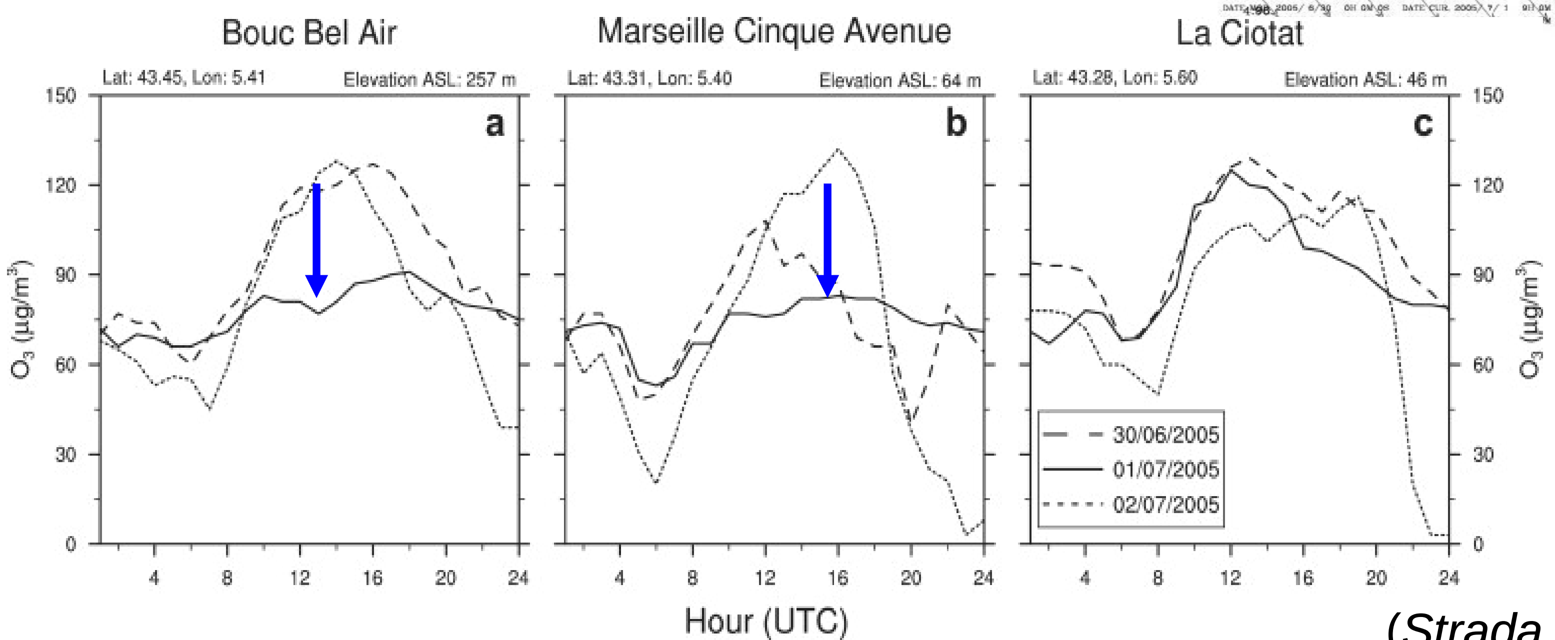
Wildland-urban interface fires: signatures on air pollution

The Lançon 2005 fire (600ha):

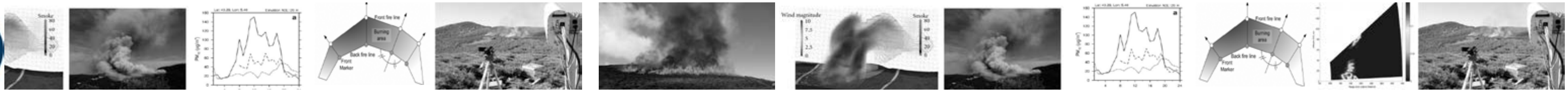
O_3 depletion in Marseille AQ stations

Smoke plumes at the surface



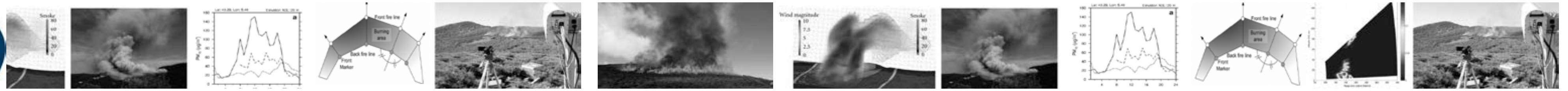


(*Strada et* al., 2012)



The AULLENE 2009 fire

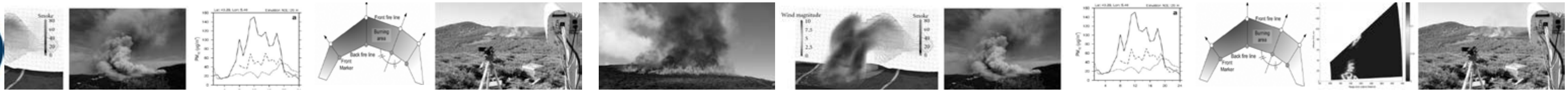
3500 ha – 900 proc – 24 millions of grid points



Outlooks

Weather-fire behavior model coupled with online atmospheric chemistry

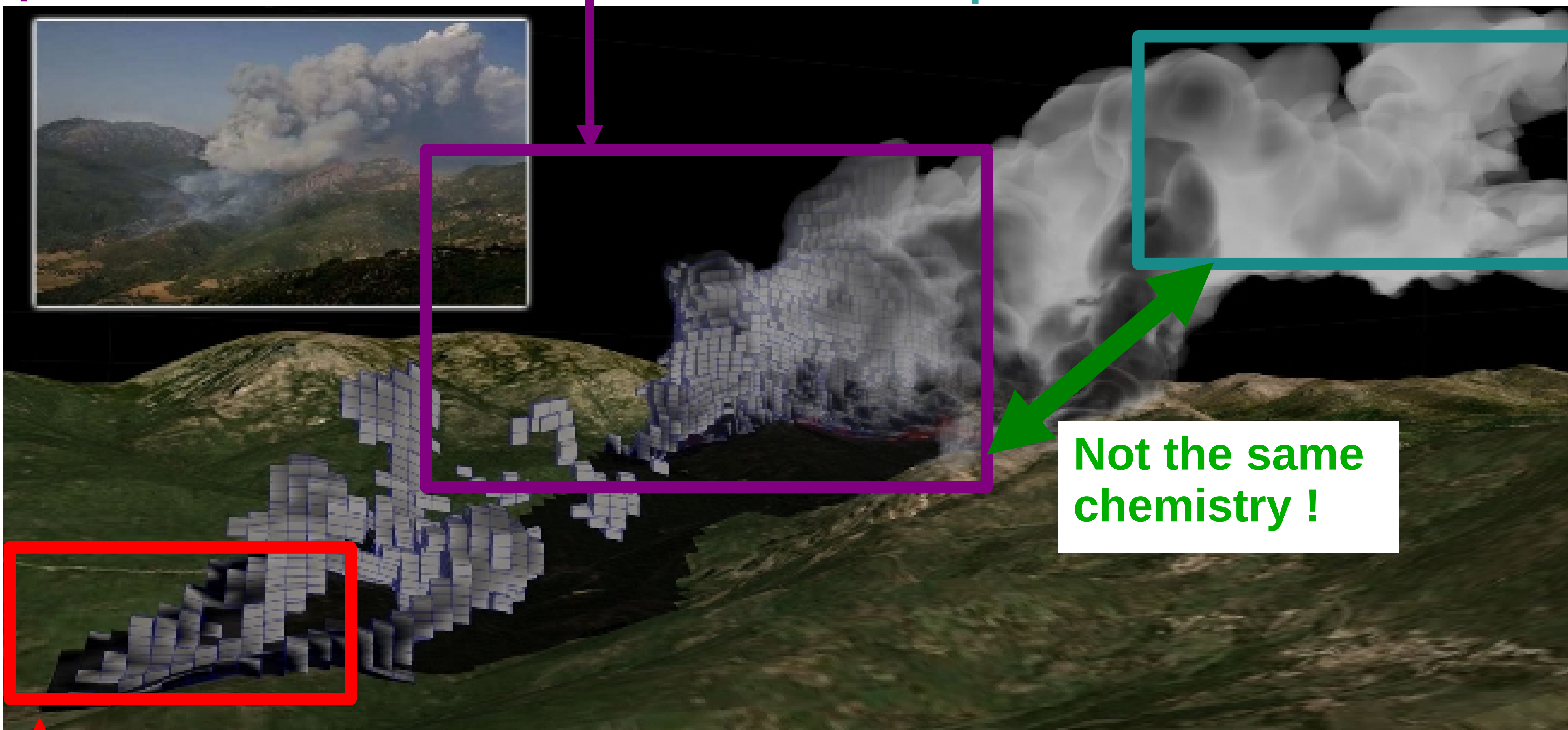
- large Euro-Med fires
- test chemistry & aerosols → smoke radiative forcing
- assess fuel properties (humidity, density, vegetation type, emission factors …) at high resolution



The ideal experiment ?

Young smoke plume: aircraft, drones, ground lidar / FTIR spectrometer, in-situ obs.

Aged smoke plume: aircraft, airborne lidar / FTIR spectrometer / satellite



Sources:
Emission factors, burnt area, fire power
Fuel characteristics

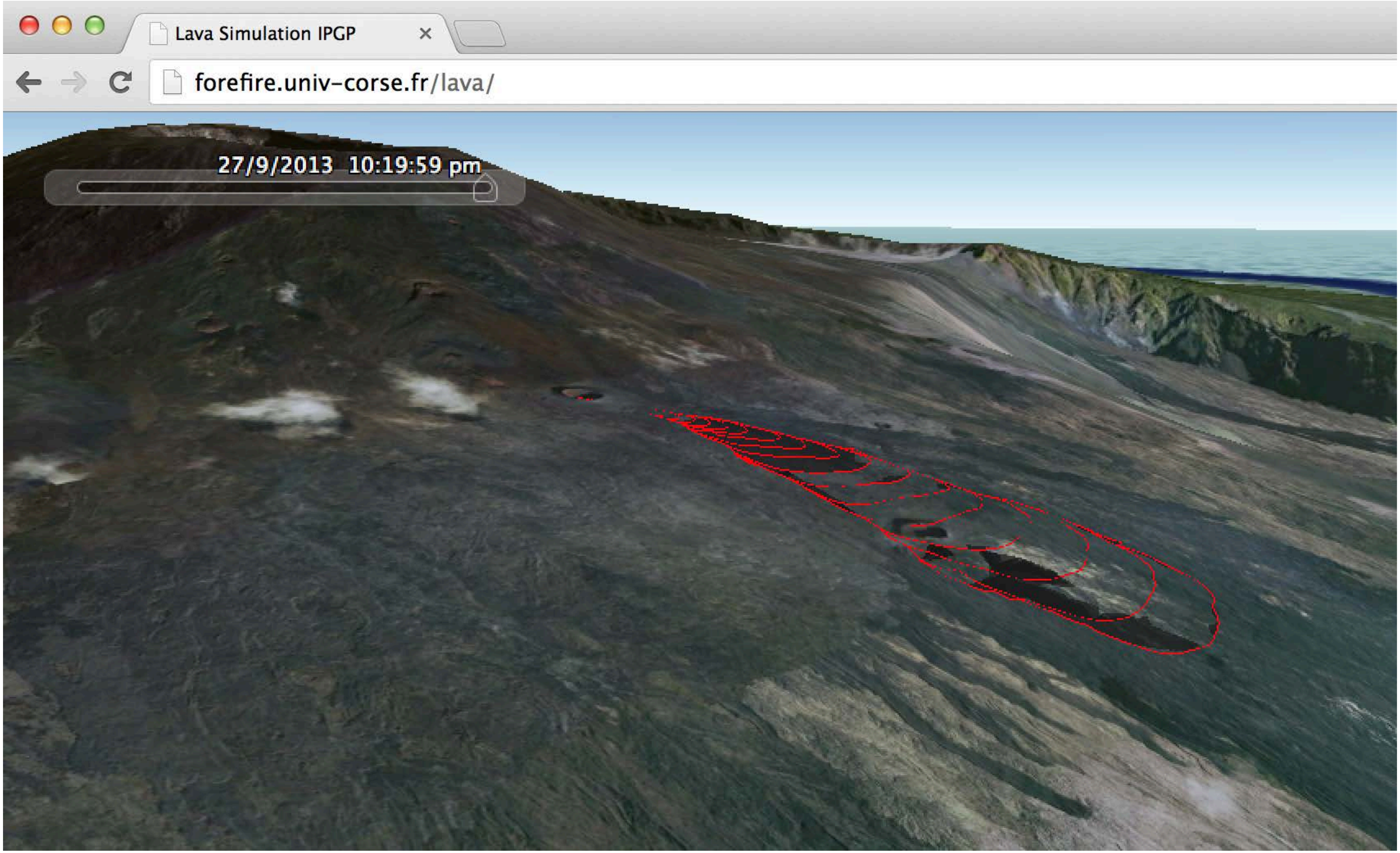
Application to Volcanoes – Piton de la fournaise With P.Tulet, J. Durand

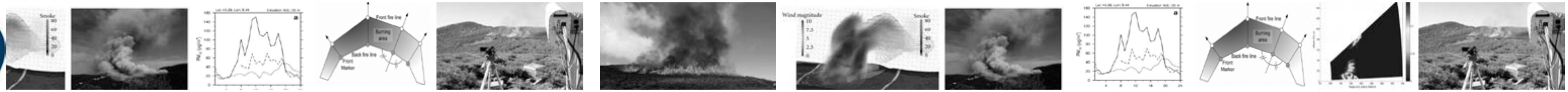
Surface Fluxes over Lava, heat and C02

Volcanoes – Piton de la fournaise With P.Tulet, J. Durand **LaCy**

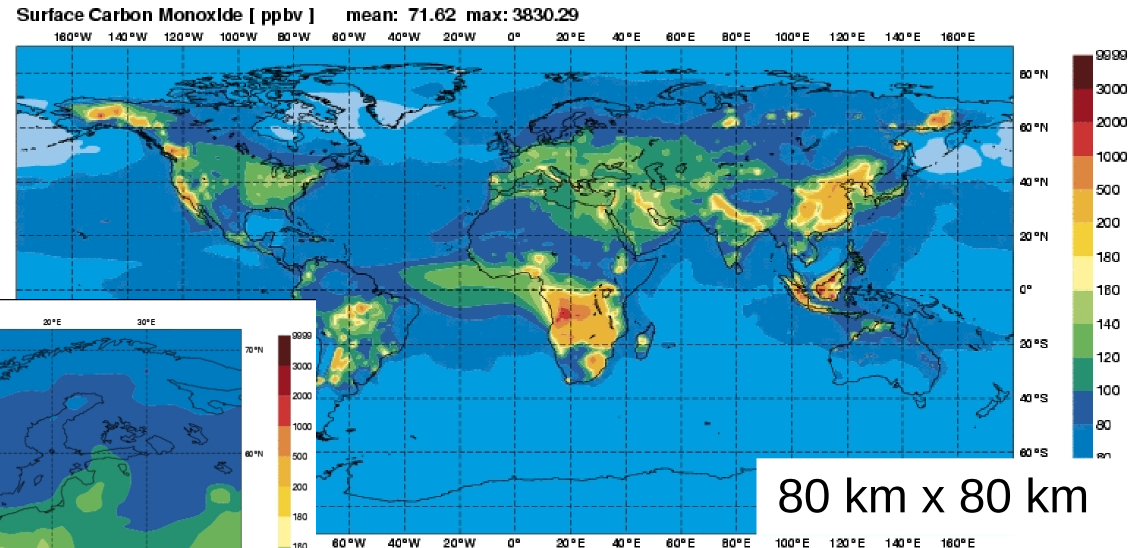
Lava spread model

Try it online : http://forefire.univ-corse.fr/lava

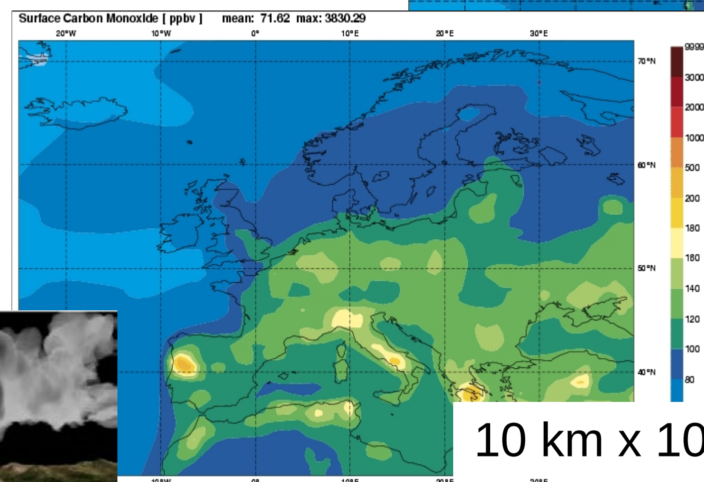




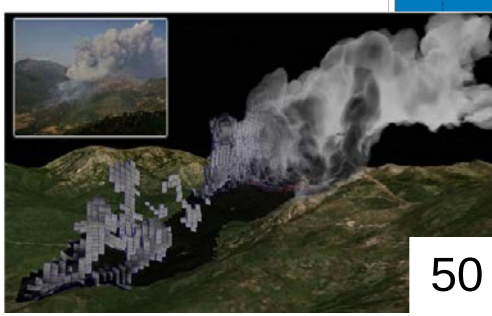
Fire and air pollution: from local to global scale



80 km x 80 km



10 km x 10 km



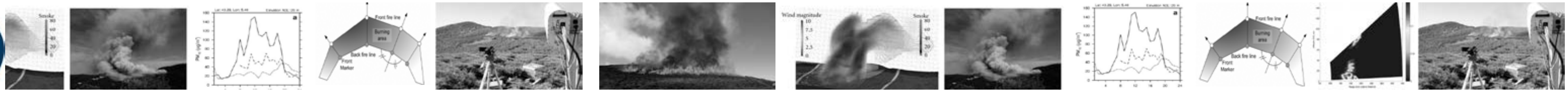
50 m x 50 m

IBBI

- Sources (dynamical emission factors, burnt area, …)

- Plume dynamics (injection height: explicit vs. parameterized)

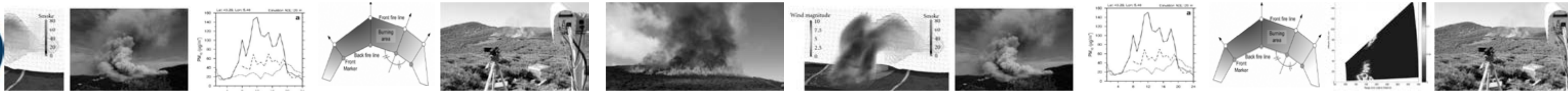
- Subgrid-scale chemistry (ozone regime, ...)

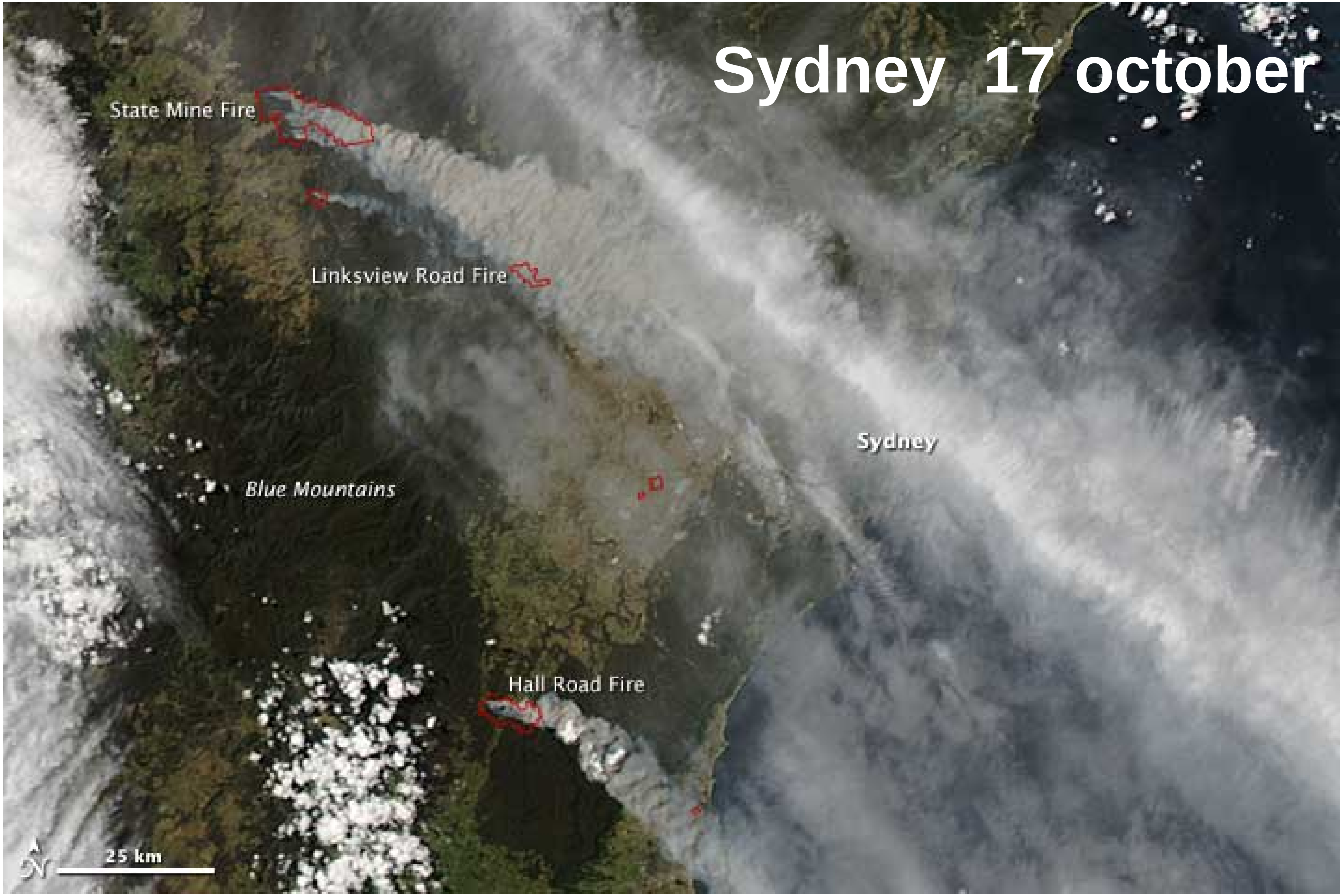


Conclusions / Questions.

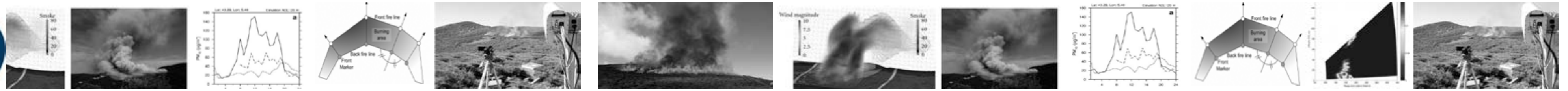
- Goal of such models: simulate very local intense micro-meteorological effects and pollution of wildfire.
- May help sub-mesh parameterization of global model by performing **reference simulation** of large wildfires.
- Use of High-Resolution models for parameterization of injection height ? By model reduction ?
- Is there too little carbon in Mediterranean fires ? any use of high resolution simulation of boreal forest ?
- Dataset of well studied fire events of use for emissions?
- Use of fire simple fire propagation model for simulation of combustion dynamics.

(*Modis 17/10/2013*., 2012)



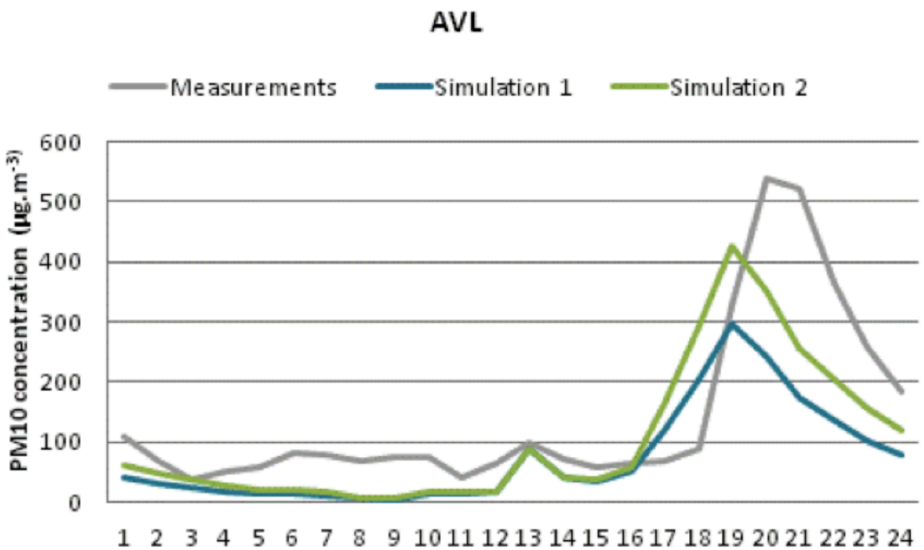


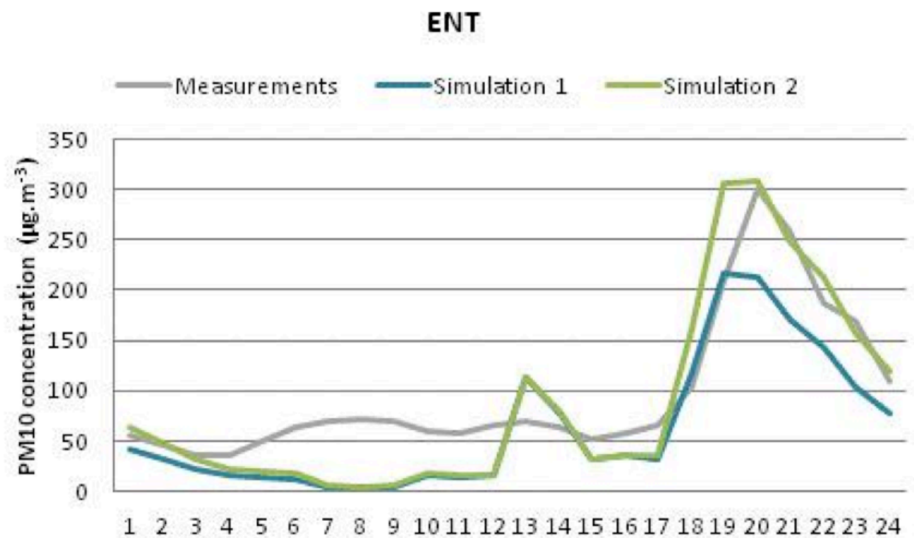
(*Modis 17/10/2013*., 2012)



The air quality modeling system **LOTOS-EUROS** was forced by

- Farsite → Simulation 1
- ForestGreen → Simulation 2



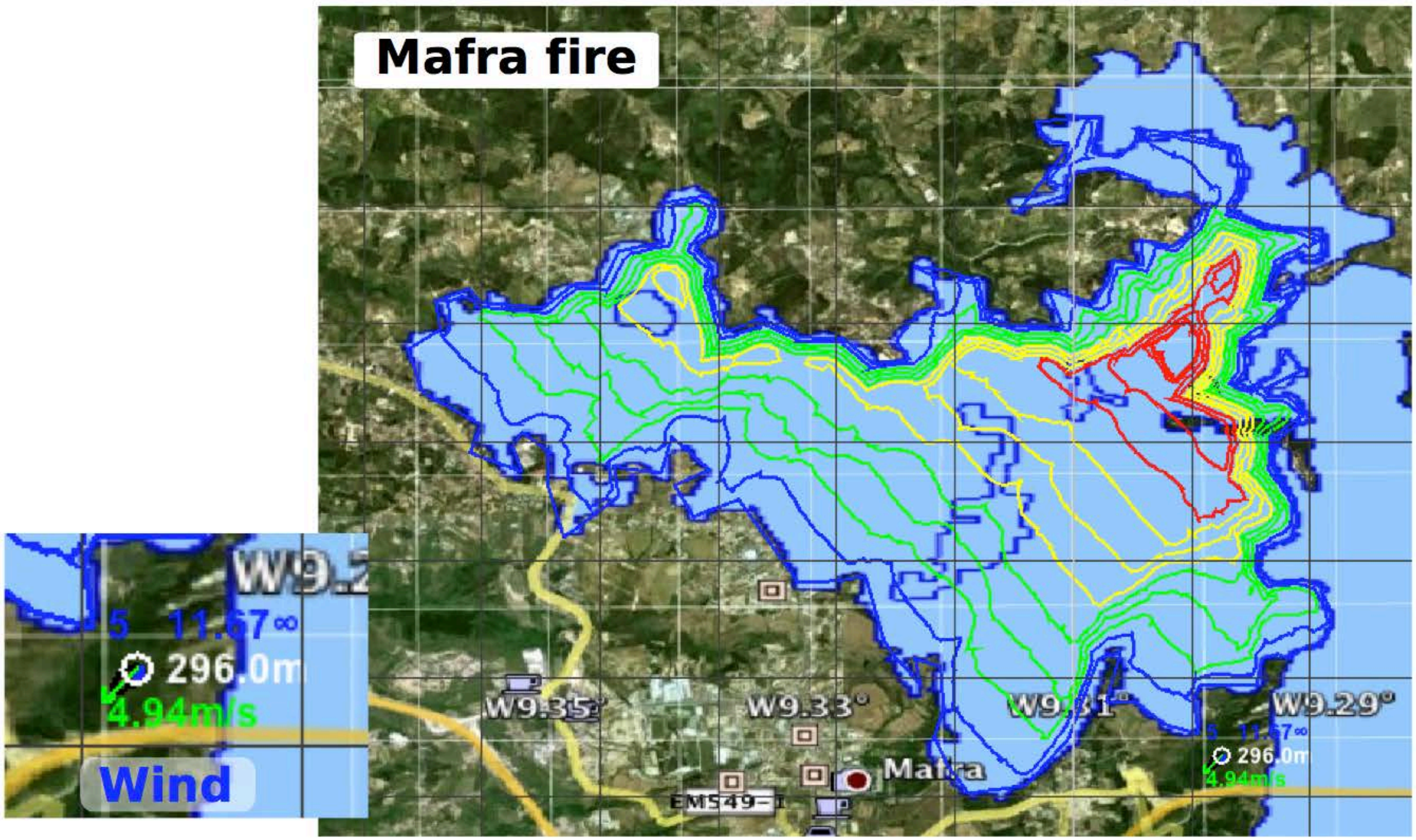


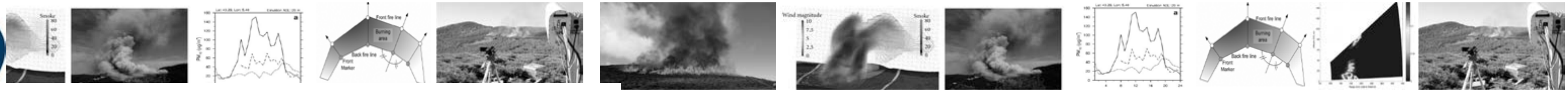
Simulated concentrations reproduce with **good timing and intensity** the high PM_{10} concentrations observed in Lisbon (AVL & ENT)

Uncertain locations for the Mafra and Loures ignition points

⇓

ForeFire applied **backward in time**
by providing the final fire perimeter and a constant wind





Fire physics – Rate of Spread

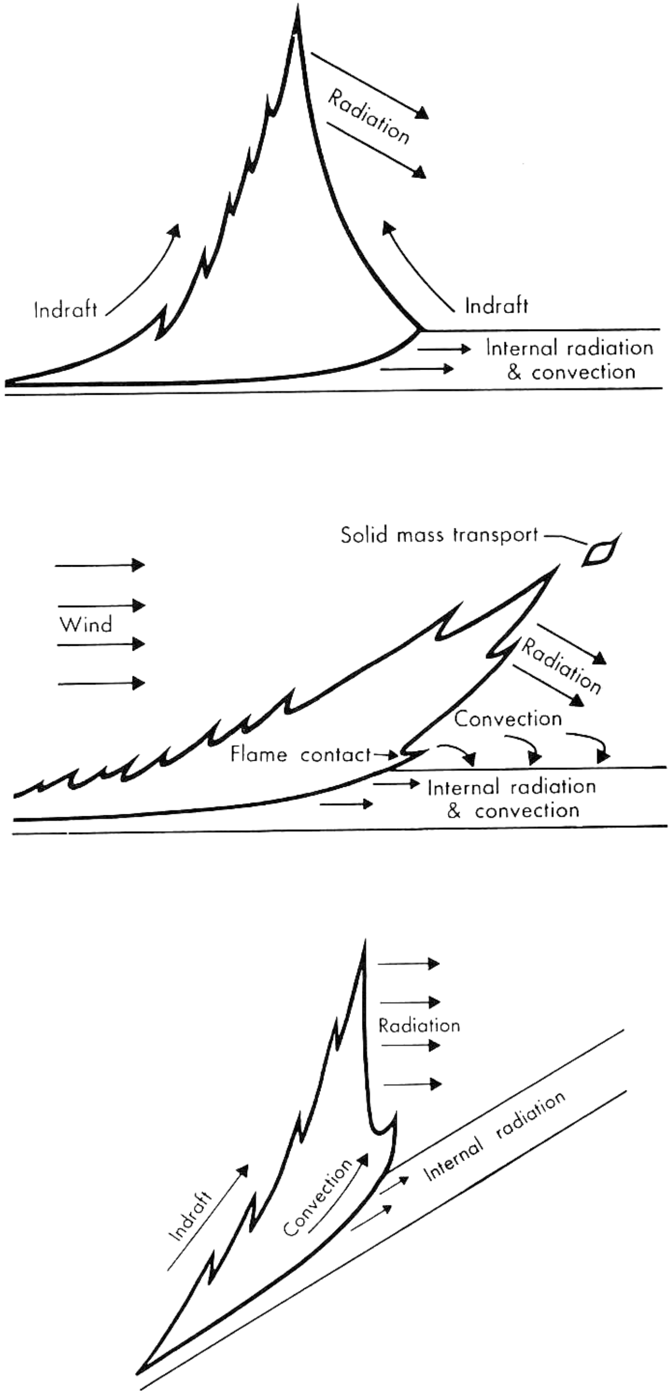
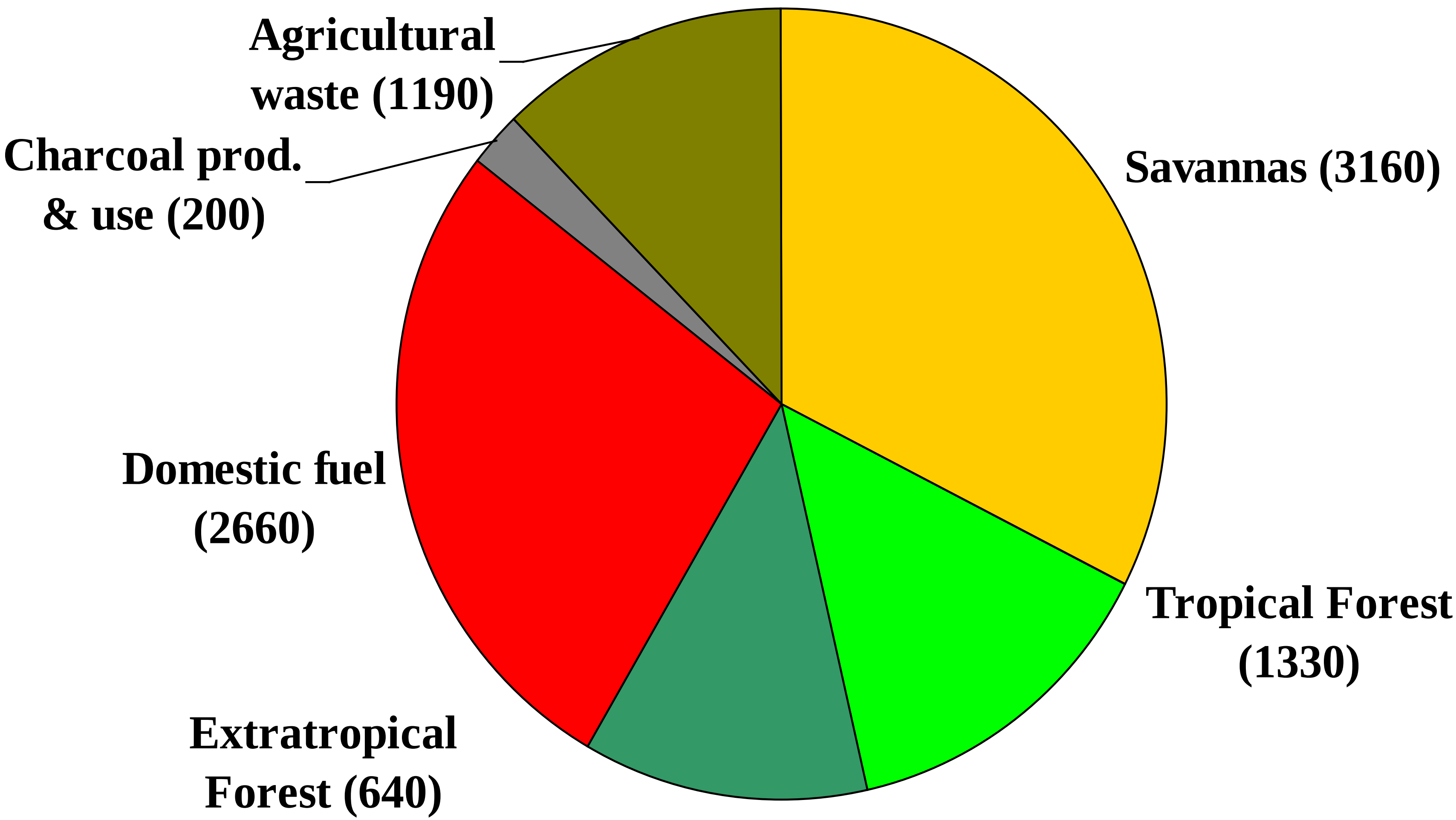


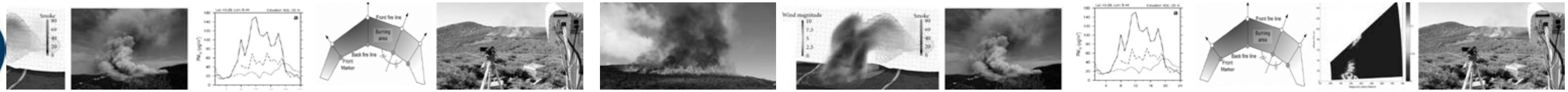
Figure 1.26. *Schematic of no-wind, wind-driven, and upslope fires.* From Rothermel (1972).

$$R_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

Vegetation Biomass Burned Worldwide:
9.2 billion tonnes (metric) annually



Source: Andreae and Merlet (2001)



From fires to chemical emission: FRE x Conversion factor

Conversion factor ~ constant

FRE from satellite:

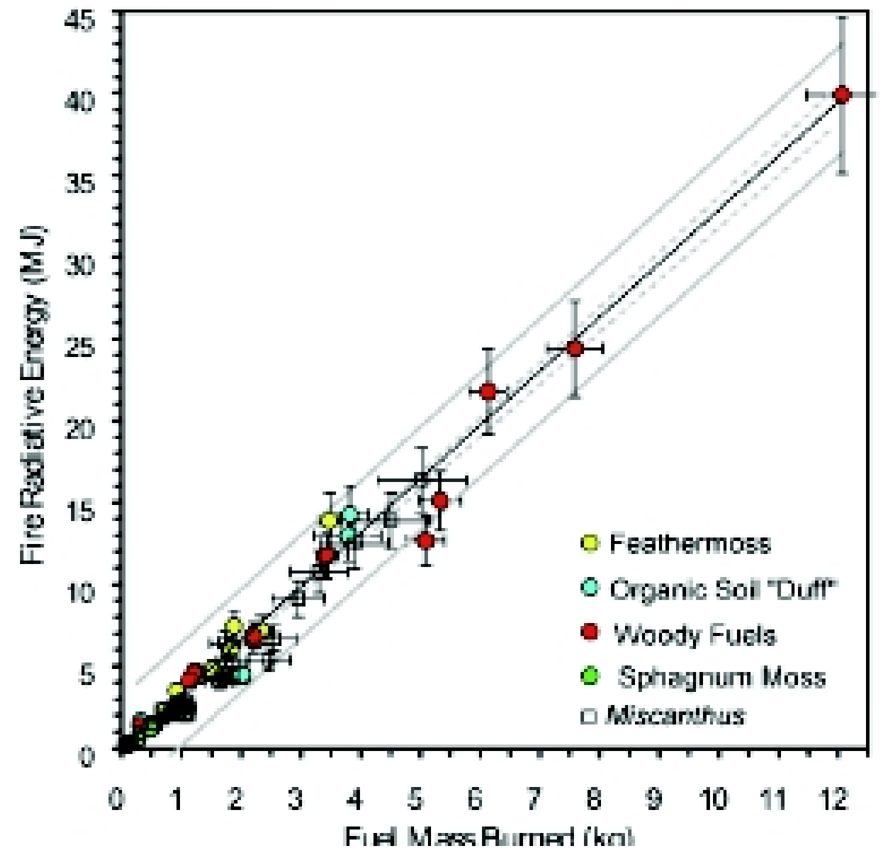
FRP=Fire Radiative Power (W)
FRE=Fire Radiative Energy (J)=∫FRP(t)dt

FRP from Meteosat/SEVIRI and Terra&Aqua/MODIS

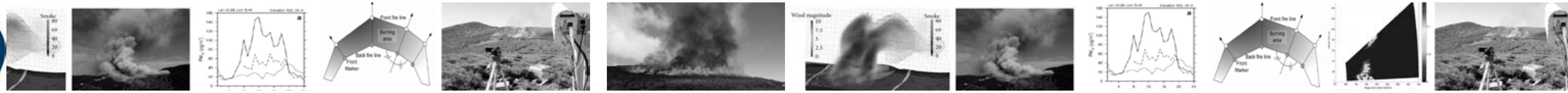
Resolutions:
- MODIS (500m ~ 25ha)
- SEVIRI (3km ~ 900 ha / 15min)

++ Reduce dependence on land cover knowledge

– - Limitations:
- cloud free atmosphere
- sampling frequency
- saturation over intense fires

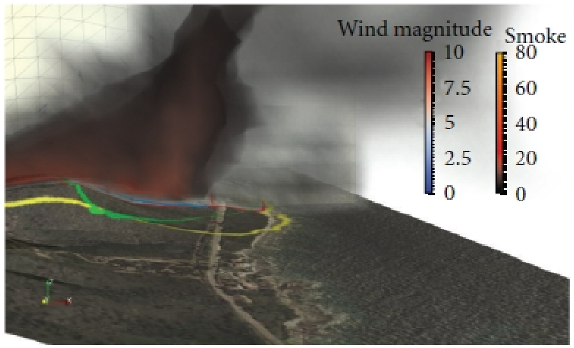


graphics by M. Wooster



Is fire propagation rate sensitive to the fire-atmosphere coupling?

Example: The Favone fire (25ha)



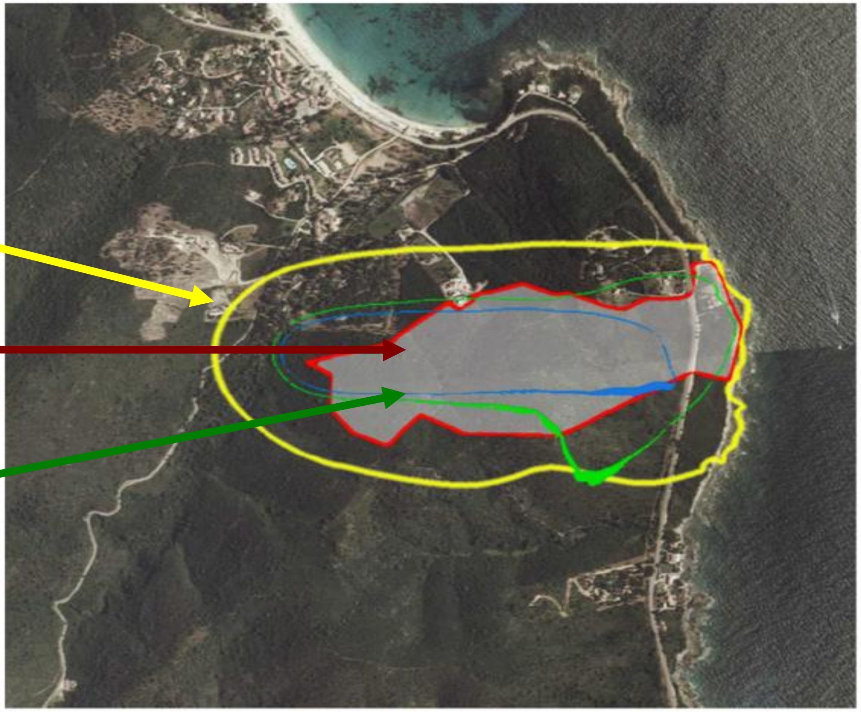
$\Delta x = \Delta y = \Delta z = 50m$
Domain size:
2.5 km x 2.5 km x 1.5 km
Duration: 4 hours
Homogeneous mediterranean schrubs
Passive tracer to mimic the smoke plume

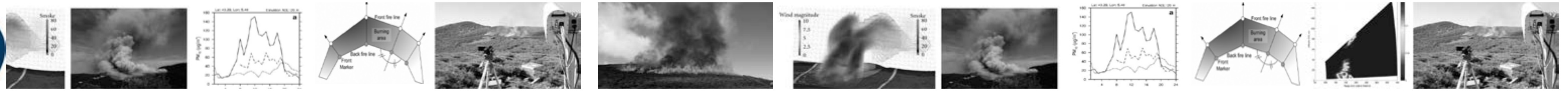
Fire contour:

Non-coupled simulation

Observation

Coupled simulation





Fires at the global scale

Fire perturbs a greater area over a wider variety of biomes than any other ‘natural’ disturbance (millions of km² per year) .

Major C cycle and landcover/biodiversity impactor – with strong influence on radiative budget and atmospheric chemistry.

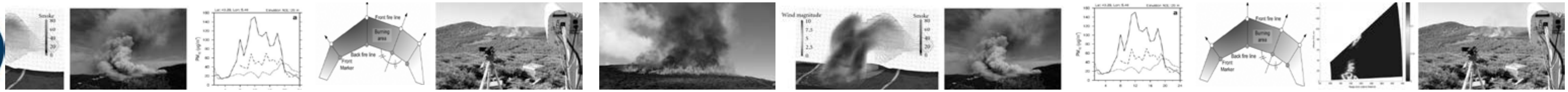
Annual C emissions from BB maybe 50% of those from fossil fuel burning. Post-fire, re-growth at varying rates reabsorbs C.

Large (~ x 10) interannual variability in key regional C emissions, together with v. strong seasonal and diurnal cycles.

Atmospheric CO_2 growth rate interrannual variation maybe strongly linked to interannual variability in fire activity.

Fire and climate interact – with potentially feedbacks.

Wooster M., King's College



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

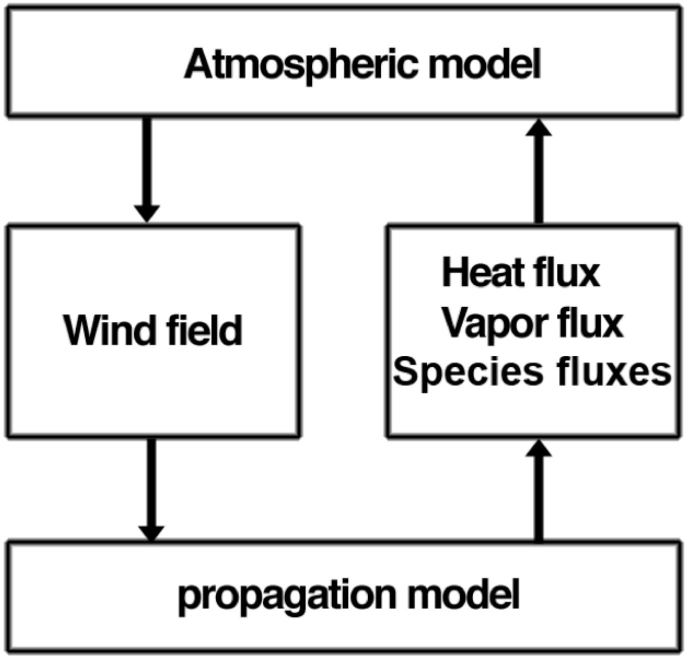
- Gamma approximation :

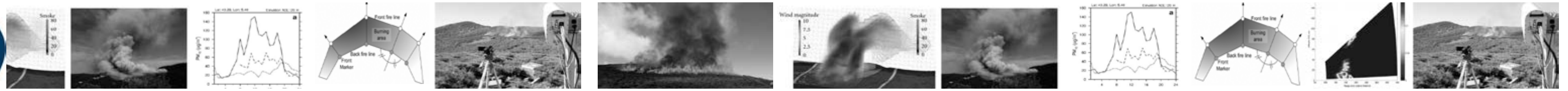
$$\Phi(\mathbf{x}, t) = \chi_b^0 exp(-4m/m_e)\Phi_{\mathbf{x}}^t$$

- 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





Heat release from Firestar

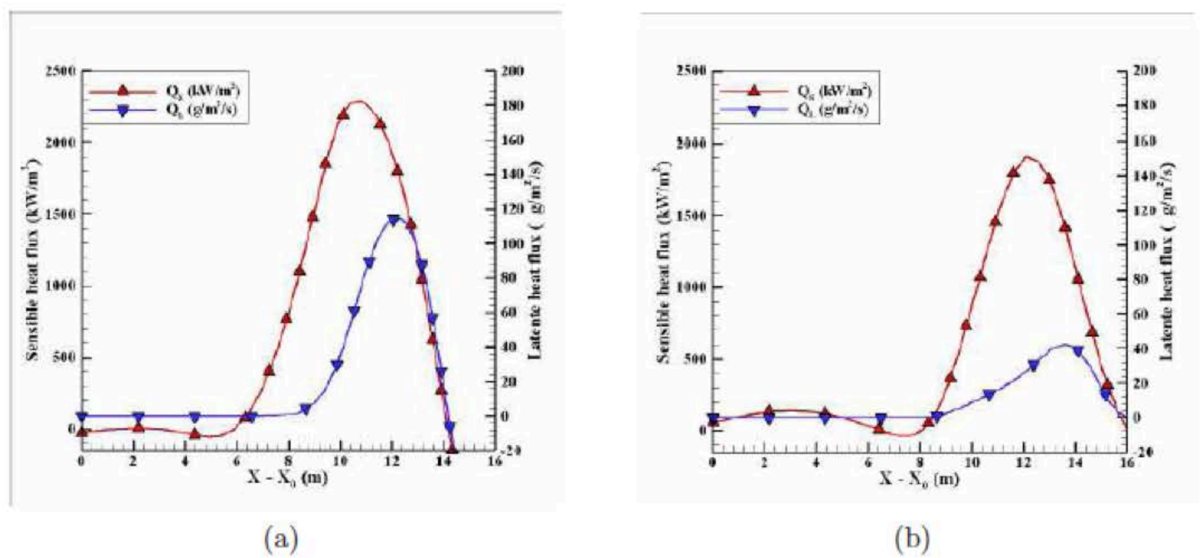
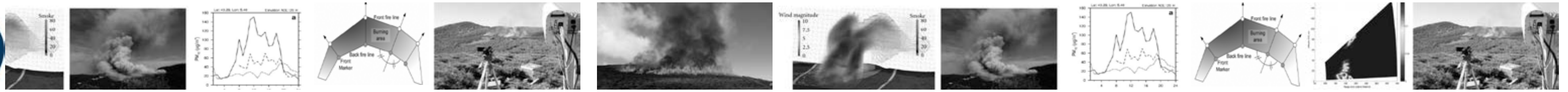


Fig. 1: Instantaneous fluxes issued from Firestar at (a) 5m high, (b) 10m high.

$$q_s(\mathrm{x},t) = A_s(\mathrm{x})(t - t^a(\mathrm{x}))\exp(-\frac{t - t^a(\mathrm{x})}{\tau_s(\mathrm{x})}),$$

$$q_l(\mathrm{x},t) = A_l(\mathrm{x})(t - t^a(\mathrm{x}))\exp(-\frac{t - t^a(\mathrm{x})}{\tau_l(\mathrm{x})}),$$

With t_a the arrival time, $A(x)$ relates to the total mass/heat at x and $\tau(x)$ the time scale of the release

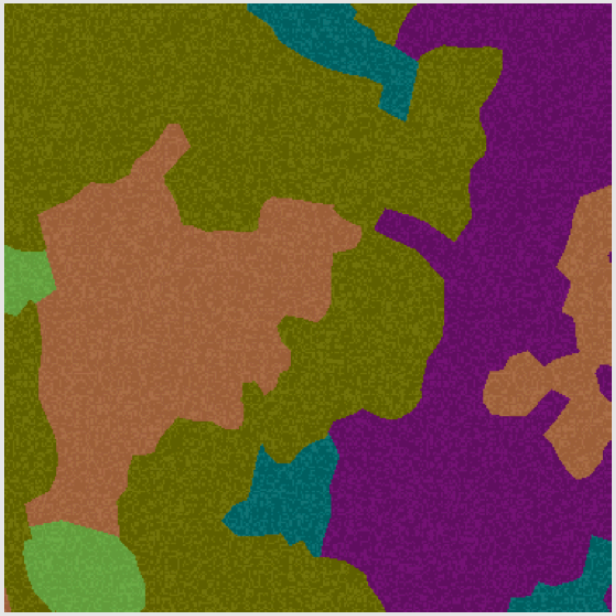


Burning map

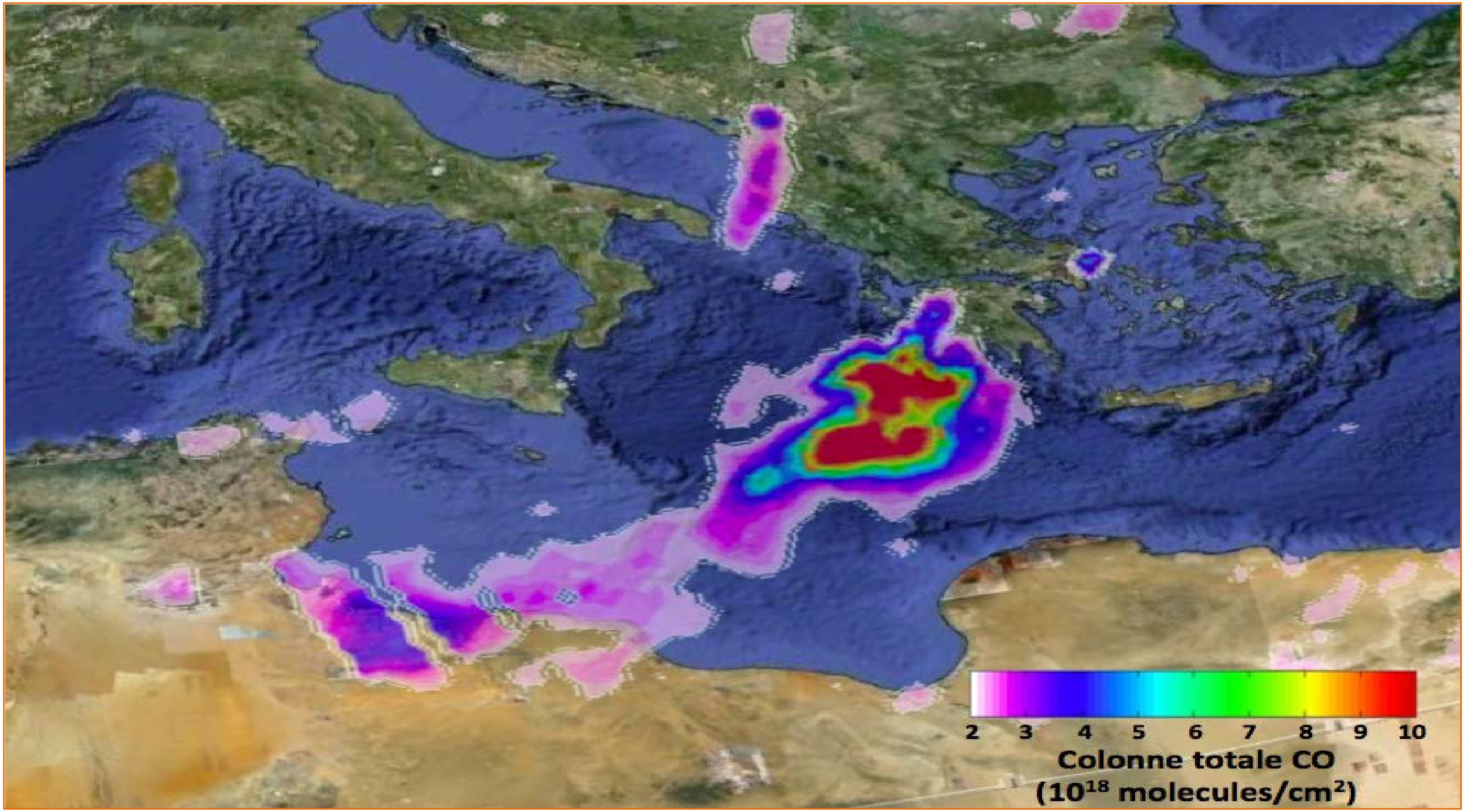
- Time of first marker occurrence,
- polygon filling method,
- updated locally at each marker update.

Fluxes layers

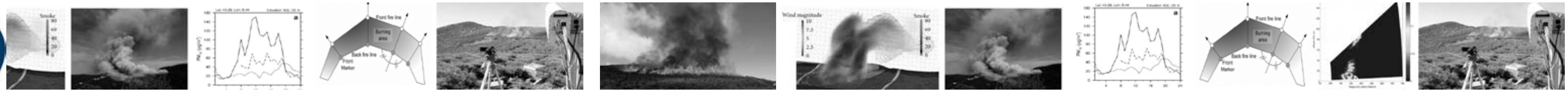
- One layer for each variable, compound,
- diagnosed as a function of actual and arrival time



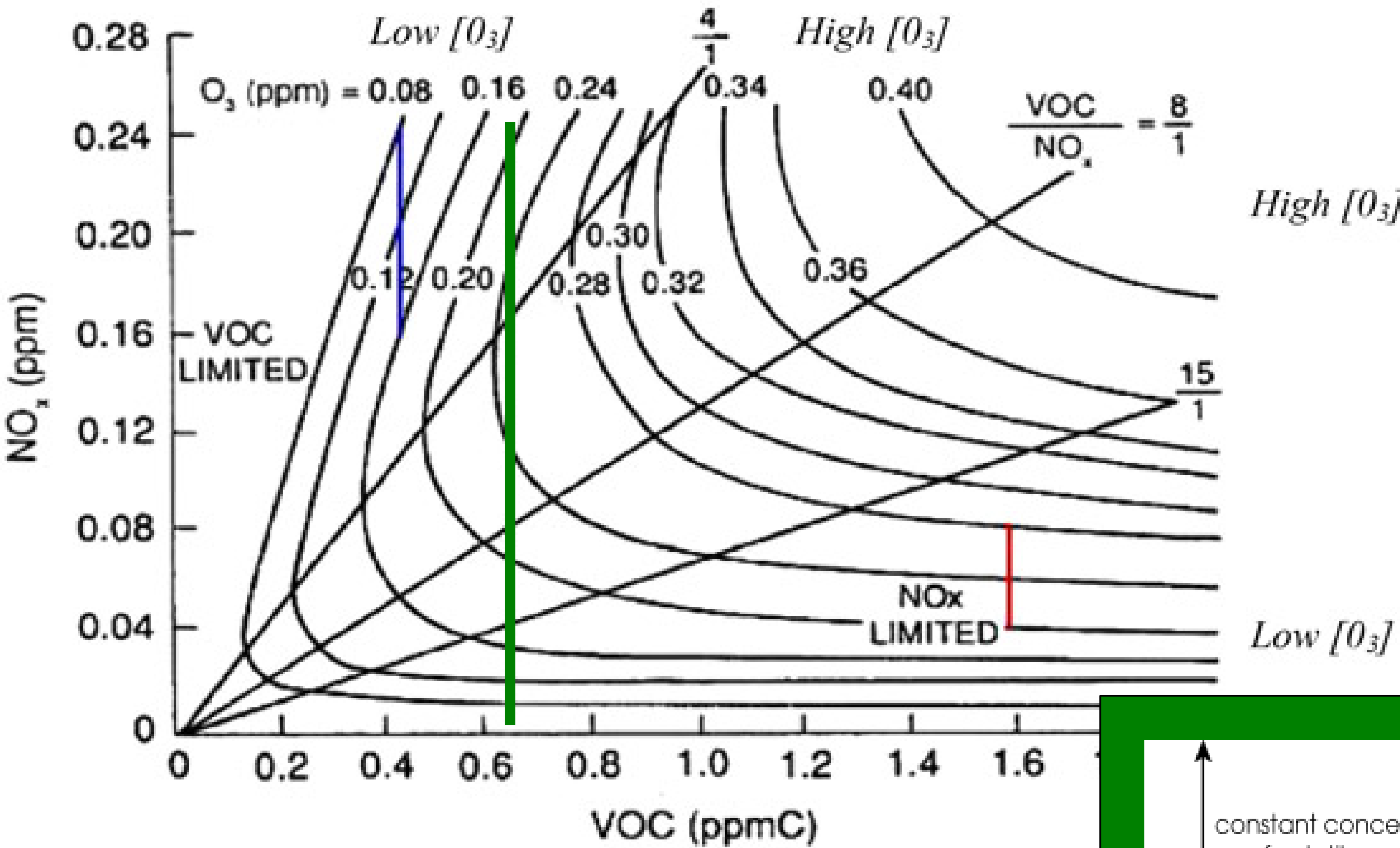
Fire impact on air pollution:
The Greek fires 2007

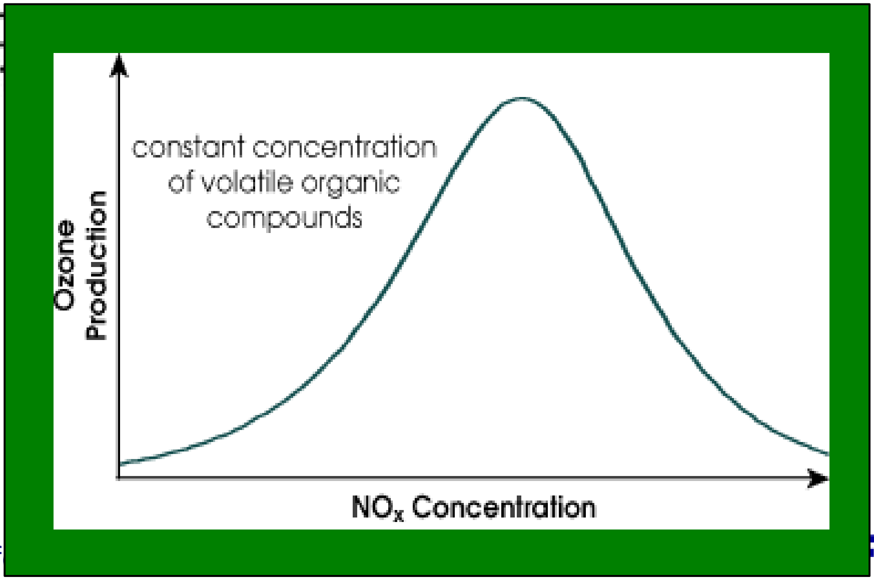


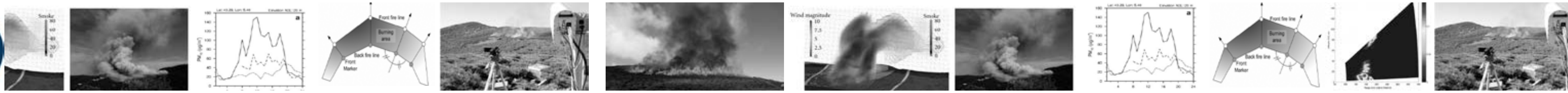
Turquety et al., 2009



Chemical aging of polluted plumes: the ozone story







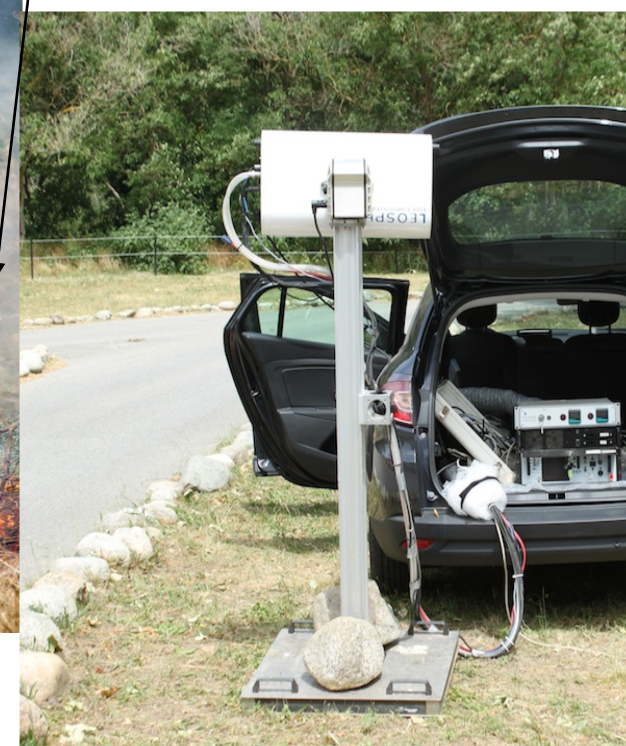
From lidar signal to aerosol mass concentration

Lidar → backscattering radiation intensity by aerosols

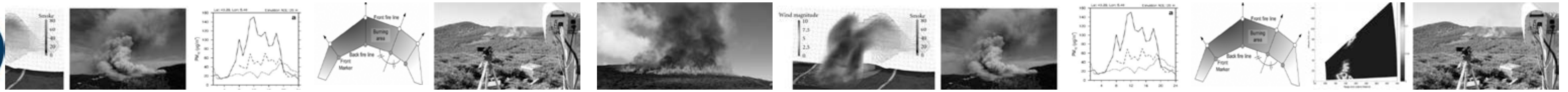
To derive aerosol mass concentrations from lidar signal: need for additional co-located simultaneous measurements (aerosols size distribution or mass concentration) → Corte 2012

CO/CO2

BC

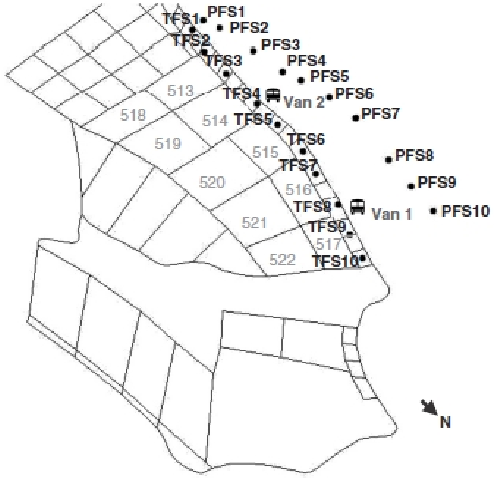


ELPI (aerosol size distribution),
particle counter,
Nephelometer, aethalometer

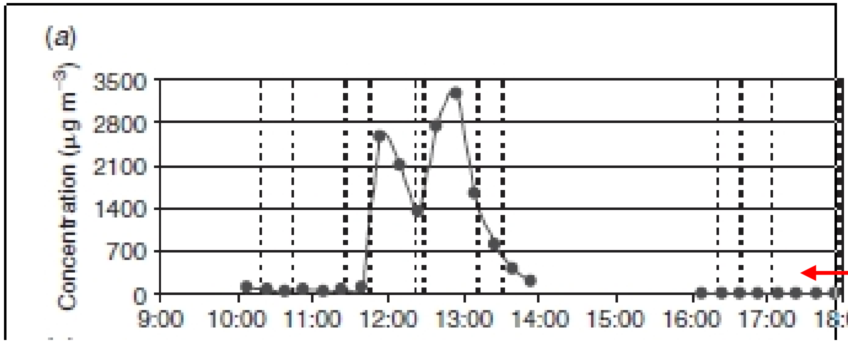


GESTOSA field experiments of fire spread in shrub vegetation including smoke observation

(Portugal: 1998, 1999, 2000, 2001 and **2002**)



→ NOx, CO, particulate matter (PM2.5, PM10), SO2, VOC



EU legislation

Miranda et al. (2005)