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# Simulation of natural complex systems, contribution to wildfire forecasting

Jean Baptiste Filippi

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UNIVERSITE DE CORSE - PASQUALE PAOLI  
**ECOLE DOCTORALE**  
Environnement et société

## Habilitation à diriger les recherches

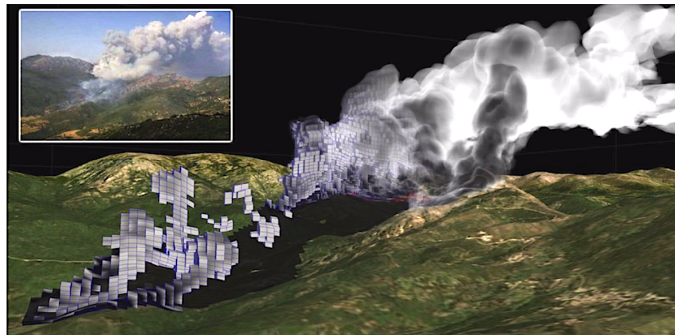
de l'Université de Corse - Pasquale Paoli

Specialité : CALCUL NUMÉRIQUE, COMBUSTION, GÉNIE  
LOGICIEL

Défendue par

Jean-Baptiste FILIPPI

Simulation de systèmes naturels complexes,  
contribution à la prévision de feu de forêt



Directeur: Albert SIMEONI

Préparée à l'Université de Corse, laboratoire SPE CNRS 6134

Soutenue le 10 mars 2021 à Corte

### Jury :

<i>Président :</i>	Jean-François MUZY	- CNRS (SPE)
<i>Rapporteurs :</i>	Denis VEYNANTE	- CNRS (EM2C)
	Francesca DI GIUSEPPE	- ECMWF
	Arnaud TROUVÉ	- University of Maryland
<i>Examineurs :</i>	Christine LAC	- CNRM (Météo-France)
	Céline MARI	- IRD
	Paul-Antoine BISGAMBIGLIA	- Università di Corsica (SPE)
	Craig CLEMENTS	- San José State University
<i>Invité :</i>	Jacques-Henri BALBI	- Professeur émérite

UNIVERSITY OF CORSICA - PASQUALE PAOLI  
ECOLE DOCTORALE  
Environnement et société

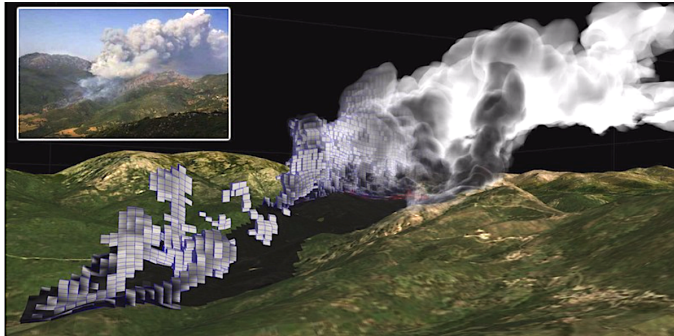
**Habilitation à diriger les recherches**

of the University of Corsica - Pasquale Paoli  
Specialty : NUMERICAL SIMULATION, COMBUSTION,  
COMPUTER SCIENCE

Defended by

Jean-Baptiste FILIPPI

**Simulation of natural complex systems,  
contribution to wildfire forecasting**



Thesis Advisor: Albert SIMEONI

Prepared at Università di Corsica, CNRS SPE laboratory  
Defended March, 10th, 2021 in Corte

**Jury :**

<i>President :</i>	Jean-François MUZY	- CNRS (SPE)
<i>Reviewers :</i>	Denis VEYNANTE	- CNRS (EM2C)
	Francesca DI GIUSEPPE	- ECMWF
	Arnaud TROUVÉ	- University of Maryland
<i>Examinators :</i>	Christine LAC	- CNRM (Météo-France)
	Céline MARI	- IRD
	Paul-Antoine BISGAMBIGLIA	- Università di Corsica (SPE)
	Craig CLEMENTS	- San José State University
<i>Invited :</i>	Jacques-Henri BALBI	- Emeritus



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## Remerciements

Je voudrais tout d'abord remercier Albert, déjà pour ta direction dans cet exercice, mais aussi parce que c'est ton dynamisme, enthousiasme et implication qui m'ont motivé au début ces travaux de recherches, puis ta jovialité et curiosité qui ont su tisser, lors de ces voyages les connexions nécessaires à leur réalisation et enfin ton amitié toujours présente.

Je remercie aussi Francesca di Giuseppe, Arnaud Trouvé et Denis Veynante pour l'honneur d'avoir reçu leurs rapports et avis. Je me souviens en particulier, Denis, que tu avais envisagé l'usage de supercalculateurs pour la prévision d'urgence en incendie avant que ces travaux ne débutent, et te remercie particulièrement (ainsi que l'IDRIS et le CINES) pour ta vision et tes actions dans les différentes fonctions que tu as pu occuper depuis, mettant à disposition ces moyens de calculs.

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Ces travaux n'auraient pas pu être réalisés sans collaborations, celle instaurée avec Vivien Mallet est certainement la plus importante car toujours marquée de créativité, mais aussi de rigueur, pertinence, culture et amitié qui m'on fait tant apprendre. Je remercie aussi Pierre Tulet qui m'a invité à la réunion à travailler sur des phénomènes encore plus intenses que les incendies, poussant ces approches couplées à leurs limites.

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Le soutien financier de l'ANR et le cadre matériel et humain offert par le CNRS, les membres de l'équipe Feu, le laboratoire SPE dirigé par Paul-Antoine Santoni, l'université de Corse et le territoire ont fortement contribué à ce travail. Je tiens à les en remercier. Je remercie en particulier Emilie Garel pour l'aide et le soutien apporté pendant la rédaction et pour la relecture de ce document, Marie-Laure Nivet et Marie Françoise Saliceti pour l'aide pendant la soutenance. J'aimerais aussi souligner le support proactif et efficace des pôles administratif et informatique du laboratoire et de l'université.

Je voudrais remercier ma famille pour leurs encouragements et Alexandra pour son soutien et sa patience au quotidien. Bravo enfin à mes enfants Matthieu et Théo pour leur blagues et bonne humeur pendant que leur père rédigeait ce manuscrit.



# Contents

<b>I</b>	<b>Curriculum Vitae and production</b>	<b>1</b>
<b>1</b>	<b>Curriculum Vitae</b>	<b>3</b>
1.1	Research activities . . . . .	5
1.1.1	Discrete events front tracking wildfire simulation code . . . . .	5
1.1.2	Coupled wildand-fire/Atmosphere . . . . .	5
1.1.3	Urgent computing and wildfire forecast . . . . .	6
1.1.4	Probabilistic forecast and wildfire danger . . . . .	7
1.2	Teaching Activities . . . . .	7
<b>2</b>	<b>Research Supervision, Programs and Dissemination</b>	<b>9</b>
2.1	Supervision . . . . .	9
2.2	Research Management . . . . .	11
2.3	Collaborations . . . . .	12
2.4	Dissemination . . . . .	13
<b>3</b>	<b>Scientific Production</b>	<b>17</b>
<b>II</b>	<b>Research activities</b>	<b>25</b>
<b>4</b>	<b>Discrete events simulation of environmental complex systems</b>	<b>27</b>
4.1	Discrete events simulation of drifting seaweeds . . . . .	28
4.1.1	DEVS Modelling methodology . . . . .	29
4.1.2	Lagrangian discrete event particle-tracking trajectory model . . . . .	31
4.2	Specification of wildfire models and simulation framework . . . . .	33
4.2.1	General description . . . . .	34
4.2.2	Specification formalism . . . . .	34
4.3	Wildfire model representation and simulation evaluation . . . . .	37
4.3.1	Representation and of a Fire Front and Notation . . . . .	37
4.3.2	Evaluation of wildfire simulation . . . . .	39
4.3.3	Model evaluation on large fire database . . . . .	41
4.4	Conclusion . . . . .	43
<b>5</b>	<b>Wildfire simulation and forecast</b>	<b>45</b>
5.1	Wildfire simulation . . . . .	46
5.1.1	Wildfire front velocity models . . . . .	47
5.1.2	Front tracking the fire . . . . .	50
5.1.3	Computation of front properties . . . . .	56
5.1.4	Parallelization . . . . .	60
5.1.5	ForeFire Open-Source Code and API . . . . .	61
5.2	Coupling fire and atmosphere . . . . .	63

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5.2.1	Meso-NH atmospheric model . . . . .	64
5.2.2	Coupling atmospheric and wildfire models . . . . .	65
5.2.3	Validation on the FireFlux experiment . . . . .	66
5.2.4	Simulation of large wildfire . . . . .	73
5.2.5	Coupled Atmosphere/lava eruption . . . . .	84
5.3	Uncertainty quantification . . . . .	87
5.3.1	Generation of an ensemble of simulations . . . . .	87
5.3.2	Calibration of an ensemble of simulations . . . . .	88
5.3.3	Results of calibrated ensemble of simulations . . . . .	89
5.4	FireCaster wildfire forecasting system . . . . .	91
5.4.1	FireCaster and urgent computing context of fire forecasting . . . . .	91
5.4.2	Daily forecast . . . . .	92
5.4.3	Fire alert short-cast . . . . .	93
<b>III</b>	<b>Summary and Perspectives</b>	<b>99</b>
<b>6</b>	<b>Synthesis and perspectives</b>	<b>101</b>
6.1	Synthesis of research activities . . . . .	101
6.2	Perspectives . . . . .	104
6.2.1	Short-term perspectives and ongoing developments . . . . .	104
6.2.2	Future developments . . . . .	107
6.2.3	Synthesis of perspectives . . . . .	109



## Preamble

This manuscript has been prepared for my application to the degree of Habilitation à Diriger des Recherches from the Università di Corsica Pasquale Paoli. The document is organized with three parts and 6 chapters. The first part contains a Curriculum Vitae followed by a summary of the codes developed, teaching, and research activities. Chapter 2 details the opportunities I had to coordinate two national research programs, participate to different funded projects and to the supervision 3 PhD students. Part one ends with a list of publications and conferences in Chapter 3. My research activities are presented in section two, with chapter 4 detailing the more computer oriented approaches initiated in modeling and discrete event simulations of complex natural systems. These led to my main current research theme in geophysics and combustion developed in Chapter 5 : Forest and wildfire simulation and forecast. After synthesizing the different contributions, the third part of the manuscript describes a new set of scientific objectives and my future projects planned at SPE laboratory along with ongoing activities to achieve them.



## Part I

# Curriculum Vitae and production

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# Curriculum Vitae

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## Research Interests

Modeling and simulation of environmental systems. Extreme weather simulation. Wild-fire simulation. High Performance computing. Fire-weather simulation. High resolution weather forecast. Data management. Uncertainty quantification.

## Contact Information

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**IdHAL** [https://www.researchgate.net/profile/Jean\\_Baptiste\\_Filippi](https://www.researchgate.net/profile/Jean_Baptiste_Filippi)

## Positions

**2006-Current** Researcher (Chargé de recherches CNRS) SPE UMR 6134 Sciences pour l'Environnement Laboratory, Università di Corsica.

**2005-2006** Engineer ECMWF, European center for medium range weather forecast, Reading, United Kingdom

**2004-2005** Post-Doctorate candidate (Japanese JSPS Grant), University of Tokyo, Japan

## Education

**2004** French Qualification aux fonctions de maître de conférences, Section 27 (Informatics) and 61 (Software engineering), UMR CNRS SPE 6134, University of Corsica, France.

**2000-2003** PhD in environmental and computer science. Une architecture logicielle pour la multi-modélisation et la simulation à événements discrets de systèmes naturels complexes. Under the supervision of Paul-Antoine Bisgambiglia. University of Corsica, France.

**2000** Master (French 5th year degree) in Computer Science, University of Corsica, France.

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**1999** Master (Swedish 4th year degree) in «Business and Computer Science», University-college of Borås, Sweden.

**1998** BA General In computer science, communication and management, Grade 2.1 (with honors), University of Coventry, England.

### Awards and grants

**2014** 2nd Bull-Fourier Prize for large coupled wildfire/weather simulations, The team presented for this prize was made up of Jean-Baptiste Filippi, Frédéric Bosseur, Christine Lac and Céline Mari.

**2004** JSPS Japanese Society for the Promotion of Science post-doctoral fellow.

**2008 July** JAMSTEC Japan Agency for Marine-Earth Science and Technology visiting grant

### Other Affiliation and Activities

- Member of the advisory board of CNRS GDR Incendie since 2016
- Member of the advisory board of MESONH Model development since 2014
- Referee : Proceedings of the Combustion Institute, International Journal of Wildland Fire; Fire Safety Journal, Atmosphere Journal, Fire Journal;
- Referee for funding agencies (project reviews): ANR since 2010
- Organizer of the Numerical Wildfire Workshop (2013 and to come in 2021)
- Sapeur Pompier Volontaire "Expert" SIS 2B (Voluntary Firefighter "expert") to perform simulation and analysis for ongoing wildfire and lesson learned documents on each major event in Corsica since 2016.
- President of the free-flying association of Corsica and tandem pilot (Since 2014)

### Bibliometric synthesis

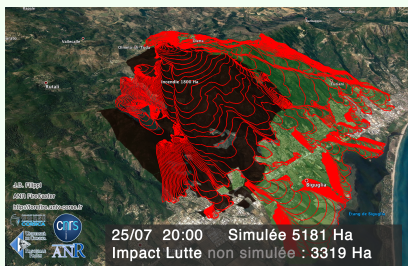
**Scopus** : H-index of 12, Publications: 22, Citations: 444

**Google scholars** : H-Index of 17, Contributions 60, Citations: 1022

## 1.1 Research activities

My research activities focus on the architecture and the methods allowing the implementation and massive exploitation of environmental simulation codes, with application ranging from seaweeds dispersion to lava flow but with a strong focus on wildfire behaviors and meteorology. For all these studies there always have been a strong requirement to be able to deliver approaches that are or can be operational and of use. The approach to fulfill this requirement was to try to combine two research disciplines, software engineering and numerical simulation in geophysics and combustion.

### 1.1.1 Discrete events front tracking wildfire simulation code



**Simulation of the Biguglia Fire (07/2017, Corsica)** as provided to fire brigades. Open-Source ForeFire simulation code is designed to compute such wildfire propagation at meter resolution in seconds.

Development and testing of discrete events front tracking ForeFire fire simulator codes, application interface and input-output routines for common geographic data types is an important result of my research work as it was used in the range of all other activities. It now represents more than 100,000 lines of code and is deployed as the French national system for wildfire behavior simulation for fire brigades. Research/Operation duality ensures better link as well as rapid feedback and commitment to work on real-world data. The originality of the work proposed on this theme is the adaptation of efficient dynamic meshing lagrangian methods to simulate fire-front propagation. It leverages the work done in the SPE Forest Fire team of modeling wildfire rate of spread for application on large fire events.

### 1.1.2 Coupled wildand-fire/Atmosphere

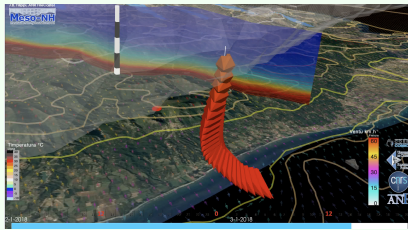


**Aullene fire (07/2009, Corsica)** Coupled fire/weather is able to catch the strong convection affecting winds around fireline. A 50 meter resolution requires 800 processor to run faster than real time.

This work was initiated in collaboration with the Centre National de Recherches Météorologiques and the Laboratoire d'Aérodologie in Toulouse. The aim of this theme is to

simulate fire weather phenomenons by coupling the mesoscale atmospheric model (Meso-NH) community code to a fire code. The main problem was to define a sub-mesh coupling strategy that can be efficiently parallelized, and define a way to specify fire to atmosphere fluxes models of heat, vapor and chemical species resulting from combustion. Resolution and scales of coupling are critical so that the energy released by the fire is not diluted over a mesh too large to allow a realistic response of the atmospheric model. Tested on data gathered on experimental fires, the coupled ForeFire/MesoNH code has proven to be able to simulate large wildfire events such as the Aullene Wildfire at a 50-meter resolution near the flame in a nested configuration up to a 600 by 720 km area. These models are now further developed to investigate complex coupled fire/weather effects (strong convection, fire induced winds).

### 1.1.3 Urgent computing and wildfire forecast

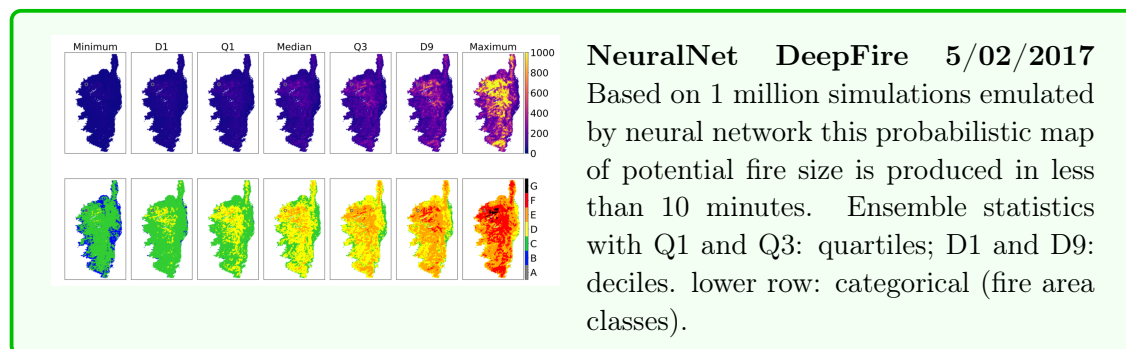


**High Resolution (600m) NowCast**  
(01/2018, Corsica) showing an extreme local Foehn effect in winter (over 30 degrees) that triggered large winter fires

While developing new codes and methods, it appeared important to specify a forecasting system design to support them. FireCaster is a collaborative research program that aims at developing this set of coherent tools, codes and methods in a pre-operational fire weather forecasting system. Basic research required to build it consist on finding this coherence (parameterization, resolutions, appropriate diagnostic methods, optimized simulation post and pre-processing). As a generalization of the previous research themes, the added complexity is to provide results on-time, with a readily available set of data, and well formatted so that it may find uses both by fire brigades and for research datasets with reproducibility. Tests and developments were performed since 2017 for the whole Corsica island and required an intensive use computer resources every day. More than 800 days were simulated and as 2017 was a very active fire season in Corsica it allowed to gather 14 large fires and fire days dataset at a unique resolution that renders other research activities possible.



### 1.1.4 Probabilistic forecast and wildfire danger



Typical fire danger rating systems relies solely on atmospheric variables, and fuel distribution is known to have an obvious strong effect if this fire danger were to be looked very locally. To overcome this limitation our approach was based on a run simulation of a fire that would start at every point of a given territory (here 1.1.4, a simulation ensemble every 80 meters on Corsica, every 10 minutes), resulting in more than 100 million simulations to perform and estimate how large fire would be in one hour. With such computation having a prohibitive cost if it were to be performed with a simulation code (about 10 seconds each), a deep neural network is required as a model emulator trained on a simulation dataset to reduce computational cost.

## 1.2 Teaching Activities

I did 50 to 60 hours of teaching per year between 2006 and 2020 at the University of Corsica, mainly in IUT (Bachelor degree) and Masters in Environmental risk (Fire and weather simulation), and Computer Science (system programming, human machine interface).

**2007-2008** IUP NTIC, Master Degree, 42h full module, System, Unix, C.

**2008-2017** Licence 3 Informatique Bachelor Degree, 32 Hours (half Module), User Interface, design and programming.

**2012-2020** IUT Hygiène et Sécurité, Bachelor degree, 18 hours Weather and Wildfire simulation, concepts, limitations and operational uses.

**2010-2018** Master in Computer Science, Master Degree, 16 hours, Human Machine interface, artificial vision, virtual reality, data, methods and code.

**2014-2020** : Master, environmental disk management, 12 hours. Use of computer models, fundamentals of numerical geophysical forecasts.

I also gave occasional courses on my research topic outside of university of Corsica :

**2012-2014** : ENSOSP (Ecole Nationale des Officiers Sapeurs-Pompiers) training (2nd national fire brigade) - Use of simulation as a tool to aid forecasting and forecast reliability (5 hours/year)

**2013** : Master Piros (Sardinia). Fire/Atmosphere Simulation (12 hours)

**2018** : Earth System Summer School, Madeira, Portugal, Wildfire in the earth system open to Portugese PhD candidates.



# Research Supervision, Programs and Dissemination

## Contents

<b>2.1 Supervision</b> . . . . .	<b>9</b>
<b>2.2 Research Management</b> . . . . .	<b>11</b>
<b>2.3 Collaborations</b> . . . . .	<b>12</b>
<b>2.4 Dissemination</b> . . . . .	<b>13</b>

### Highlights

**Coordination** Leader of one CNRS PEPS program and two large trans-disciplinary, multi-laboratory research programs fund by the ANR (French national science foundation).

**Supervision** 3 PhD students, 3 Post-Docs and 7 master students.

**Publications** 22 journal articles and 34 conference papers and talks.

**Software** Main developer of Open-Source LibForeFire wildfire solver, FireCaster API framework and early Grib-API (up to v0.8) now used in most European weather agencies.

**Operational applications** FireCaster API is the solution deployed within the French National information system of firefighting operations.

**Collaboration** 2 Thesis coordinations with 2 other laboratories and article co-authorship with 5 international and 9 national laboratories.

## 2.1 Supervision

If I did help a PhD candidate, Yutaka Kokubu, that stayed in Corsica for 6 months in 2012 and used the results developed during my Post-Doc in Japan in 2008, my first doctoral student was advised under the supervision of Paul-Antoine Bisgambiglia, Bahaa Nader, defended in 2015 on the creation of an experimental simulation framework for the evaluation of fire simulation, with part of the work being also carried out with Vivien Mallet (INRIA).

The second, Jonathan Durand started at the end of 2012 co-advised with Pierre Tulet à the LaCy lab of Université de la Réunion. Defended in 2016 his subject was the simula-

tion of lava flow and emissions following a volcanic eruption, using coupled lava/weather simulation using ForeFire/MesoNH.

I am now co-supervising a doctoral student until 2021, Frédéric Allaire at the INRIA Paris lab with Vivien Mallet (Applied Mathematics, ANGE team) under the supervision of Jacques Sainte-Marie to work on wildfire danger estimation, uncertainty quantification using simulation and deep learning.

From 2011 to 2013, I supervised Xavier Pialat's Post-Doctorate on fire simulation codes, from 2017 to 2019, Yolanda Perez post-doctorate on the theme of surface fuel parameterization and in 2020 Ronan Paugam on fuel moisture computation.

Finally, I did supervise seven master students, in atmospheric and computer sciences. One of them stayed longer, two years working part-time, Damien Grandi helped to develop the online simulation aspects and used this know-how to create his data management company.

**Bahaa Nader** (2009-2014) Evaluation de simulations de feux de forêts, 50% Co-Advisory with P.A. Bisgambiglia, University of Corsica, Corsican Regional Grant.

**Jonathan Durand** (2011-2015) Modélisation numérique du transport des panaches volcaniques de type effusif, 50% Co-Advising With Pierre Tulet, Université de La Réunion, French government ministry of research Grant.

**Frédéric Allaire** (2017-2021) Modèles de crises, estimation du risque incendie immédiat et potentiel par simulation de masse, 40% Co-Advisory with V.Mallet under the supervision of Jacques Sainte-Marie, INRIA Paris, ANR FireCaster program Grant.

Student	Period, degree (if applicable), funding, subject
Yutaka Kokubu PhD	2014 (6 Mth), Univ.Tokyo grant, Seaweeds Dispersion
Xavier Pialat PDoc	2010-12, ANR, Coupled fire Code
Yolanda Perez PDoc	2017-19, ANR, Surface fuel models
Ronan Paugam PDoc	2020 (4 Mth), ANR, Fuel moisture
Damien Grandi Msc	2013-15, Univ.Corsica, CEMER program - FireCaster API
Jeremy lefort Msc	2015 (2 Mth), E.C. Lyon, Emulation of wildfire simulation
Thomas Akkari Msc	2017 (2 Mth), Univ.Corsica, FireCaster services
Dominique Gaffory Msc	2017 (2 Mth), Univ.Corsica, FireCaster web
J.B. Vincentelli Msc	2017 (6 Mth), Univ.Toulouse, Wildfire data collection
Antonin Soulié Msc	2019 (3 Mth), Univ.Toulouse, Fuel Moisture estimation
Quentin Duriani Msc	2019 (4 Mth), Epitech, ANR, Weather FireCasts API

I have also participated in the PhD jury of four PhD Students (one defense planned).

**Suzanna Strada** July 2012, Modélisation multi-échelle des impacts des feux de végétation sur la dynamique et la chimie de l'atmosphère en région méditerranéenne. École doctorale Sciences de l'Univers, Université de Toulouse

**Mélanie Rochoux** January 2014, Vers une meilleure prévision de la propagation d'incendies de forêt : évaluation de modèles et assimilation de données. École doctorale Sciences pour l'Ingénieur, Châtenay-Malabry

**Andrea Trucchia** October 2019 reviewer for "Front Propagation in Random Media" Basque Center for Applied Mathematics Universidad del Pais Vasco

**Aurelien Costes** February 2020, Couplage bi-directionnel feu-atmosphère pour des simulations à la demande en cas d'incendies de forêt. École doctorale Sciences de l'Univers, Université de Toulouse

## 2.2 Research Management

I had the opportunity to coordinate 3 collaborative research programs, while the first one was a small starter program on a coupled fire/weather demonstrator, it created a strong trans-laboratory team that worked on two following large national research programs on wildfire sciences funded by the French agency (ANR). First the IDEA project, finished in 2014, rated "Highlight" by the ANR, to develop methods applicable to large wildfires, then FireCaster to further develop these methods in a coherent pre-operational platform. I have also collaborated in European and regional research program.

As a coordinator.

**CNRS PEPS** (15Keur) 2008-2009.

**ANR** High Performance Computing IDEA (2009-2014) (490.000 Eur) marked "High-Light program" by the funding agency.

**ANR** Environmental Challenge FIRECASTER (2016-2021) (520.000 Eur)

I have also participated in 3 research programs as a collaborator :

**European MED** , Proterina (500Keur) 2009-2013.

**LEFE** ASSIM (Wildfire data assimilation) 2010-2013

**LEFE** MoPav (Volcanic eruption) 2013-2025

Among these programs, the most important one was probably the initial PEPS "Couplage Feu-Atmosphère, étude exploratoire" that started in 2008 fund by CNRS with the same consortium that composed the IDEA program.

### IDEA program summary

Incendies de forêts : simulation de la dynamique et des émissions atmosphériques par couplage de code. Forest Fires: propagation dynamics and atmospheric emissions simulation by code coupling.

CNRM (CNRS/Meteo-France), LA (CNRS/Université de Toulouse), Inria Paris, M2P2 (CNRS/Université de Provence), EM2C (CNRS) and CECI (Cerfacs/CNRS)

As project, it succeeded to create a validated large-wildfire simulation system that takes into account the coupled effects (usually simplified in existing approaches) between combustion, propagation dynamics and meteorology. The coupling is performed by tabulation and development of a parametric combustion model of the flame, and then by nested grids from the fire front scale (mesh < 100m) to the regional scale (mesh > 1Km). This ambitious project, was based on a successful two-year exploratory study handled by the same consortium (CNRS PEPS). The main goal (i.e. scaling coupled wildfire simulation to the regional scale) required thousands of hours of computational time on meshes composed of several million points. The main purpose of the code available at the end of the project was enhancing our understanding of the phenomenon; alternatively it may also be used to propose a relevant real time wildfire simulation system triggered in case of major natural disaster. Results were presented in a meeting with operational decision makers at the end of the project and considered "HighLight" by the funding agency.

### **FireCaster program summary**

FIRE, foreCASTing and Emergency Response platform.

LISA (CNRS- Università di Corsica), CNRM (CNRS/Meteo-France), LA (CNRS/Université de Toulouse), Inria Paris, EM2C (CNRS) and CECI (Cerfacs/CNRS)

At the time funding, development of operational services dedicated to mitigate natural and anthropological risks was one of the objectives of the ANR agency call. In the frame of former IDEA, several demonstrators dedicated to wildfire risk were developed (codes, approaches, services), aiming at proposing a new generation fire decision support system. The goal of the FireCaster project was to scale these advances up to operational prototype. The resulting codes, methods and data merges in a coherent platform that allows to estimate upcoming fire risk (H+24 to H+48) and in case of crisis, to predict fire front position and local pollution (H+1 to H+12) at very high resolution in an urgent computing context. It required basic science to derive generic methods from IDEA specific developments as well as testing and validation at all scales.

## **2.3 Collaborations**

The main collaboration were within the framework of the IDEA and FIRECASTER research programs that I carried in collaboration with the CNRM (Christine Lac, Patrick Le Moigne and Valery Masson), INRIA Paris (Vivien Mallet), CERFACS (Mélodie Rochoux), the Laboratory of Aerology (Céline Mari), and LISA (Economics, Corte, Antoine Belgodère).

I also acted as a board member of the International Burning Biomass Initiative, a group to define the atlases of combustion residues emissions (natural fires), requiring in the near future the use of fire simulation codes.

I also collaborate with the University of San Jose, FireLab group of Craig Clements, who developed instrumentation in many burning experiments in the United States and participated in an experimentation campaign in Texas in early 2013 and an experiment to come in 2021. Craig Clements also did a 2 months visit in Corsica (May-June 2015) to work on the re-analysis of the FireFlux 2 experience with coupled fire-atmosphere code.

I also participated in the committee of the WUIFire (Wildland Urban Interface) program of the San Diego State university, for which I participated in the drafting of a set of research themes, in particular on the fire/atmosphere coupling.

Finally, a collaboration was reactivated for on research carried out in 2012 with Yutaka Kokubu at the University of Tokyo. The Fukushima disaster having destroyed the marine research station of this university, the final paper was finished only in 2018 once data was eventually gathered on the estimation of Sargassum algae concentration in East China Sea.

## 2.4 Dissemination

### Software and licensing

As most of my research work is on numerical simulation, I did develop several codes, scripts, post and pre-processing routines, some of which are still in use by some users, but only three can be noted as successfully disseminated with industrial application of widespread use. First the ForeFire software (DI-02 153-01) was the subject of a contract between the UMR SPE laboratory and Thalès-Aléniastospace in 2013 that generated enough funding to hire a part-time master student (Damien Grandi) to work on platform development thereafter. The second corresponds to the simulation platform "FIRECASTER API", on an architecture of data setting and simulation service on demand, now deployed as the French national system of wildfire simulation. Finally, the GRIB-API (now ec-codes) library that I started developing with the supervision of Baudoin Raoult at ECMWF is now one of the most widely used geophysical data encoding and decoding library in weather forecasting centers.

### Expertise for operational Fire Fighting activities

I have been working voluntarily as "expert" for the firefighting brigade in North Corsica since 2017 in order to perform detailed weather forecasts on ongoing fires, reanalysis on seven major wildfire events and coupled fire/weather simulation of what-if scenarios for training purposes. I am usually called to act as weather and fire behavior analyst using the running FireCaster system, and after the fire to perform simulation without some or all fire fighting actions to evaluate the efficiency of these action and quantify how much has been saved by the fire-fighters. Latest expertise were for the "Monte Grosso Fire" in august 2020 where simulation runs showed that a quick and implemented fire fighting/curing actions located ahead of the fire saved more than 3000Ha of vegetation. Latest fire weather analysis consisted in two daily bulletin for 5 days during the february 2020 extreme wind episodes that generated strong, dry, turbulent downhill winds on the south east coast of Corsica and the "Quenza" fire (500Ha). On this event, the complexity of the topography did highlight the adequacy of high resolution forecasts that became the prime forecasting source for the 4 fire brigades fighting on-site (200 fire-fighters total).

### Data visualization and interactive simulation

Besides pure basic science usages, there is also a strong expectation from fire departments and public to actually be able to use and interact results of research. I therefore took

the opportunity of some Master Students project to create scientific installations (real or online) for use with the fire-fighters, scientific fairs, web showcase or (2 per year) talks in high and primary schools. Considering the amount of data generated in all simulation efforts, visualization scripts were mostly done with Paraview [Paraview](#) for 3D, and graphics libraries in python for general plots that served as rendering platforms for all items in this section.

**Web interactive simulations:** The on-line simulation platform <http://forefire.univ-corse.fr> is the main vector for disseminating scientific know-how in the code and models as it allows students and even school students to perform wildfire simulation anywhere in France, watch the result and download google-earth file. Since online in 2015, more than 4 thousands simulation have been run by both fire brigades and general public, students and schools to learn about wildfire.

**Augmented Reality wildfire simulation sandbox** In order to provide physical interaction with the simulation, a solution was found by building an [AR Sandbox](#). Measuring about a meter in width as seen in figure 2.1, the DIY sandbox built in 2016 uses a Kinect 3D structure sensor, a video projector, and a computer with FireCasterAPI to interact with simulation on a hand modeled terrain.

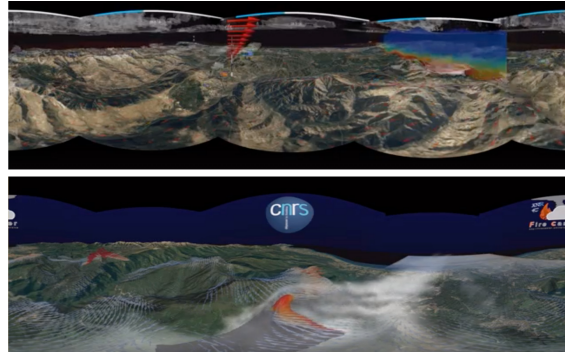


**Figure 2.1:** An AR Sandbox (left) shows a FireCasterAPI simulation (right) once illuminated with interactive video-projector

**3D Weather forecast video clips:** The FireCaster [video channel](#) provided 3D Weather forecasts calculated on the university's supercomputer daily at a rate of 6 videos per day since 2017, and specific fire weather forecasts on fire days, with a total of over 2000 forecast videos (cumulated 250 hours of scientific animations).

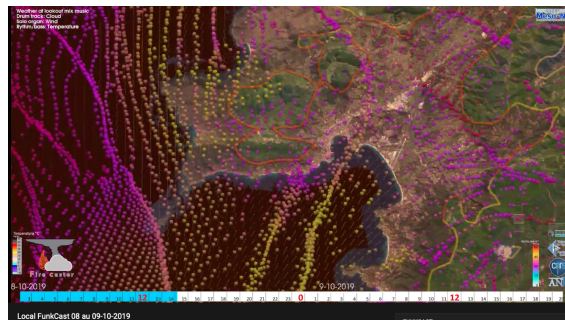
**Virtual Reality 360 animations:** 3D images from different views can be merged to generate 360 scientific animations as content for Virtual Reality headsets (and small cardboard headsets for smart phones). Figure 2.2 presents these simulations for either a weather forecast or a wildfire-atmosphere coupled simulation. All are compiled in a [360 video channel](#)





*Figure 2.2: 360 animations of a weather (top) and coupled fire (bottom) simulation.*

**Generative music for forecast:** Also an original contribution in this section was made for an art animation contest "Pixel Week-End" where we developed the **FunkCast2.3** ([FunkCast on the web click here](#)) with kids Matthieu and Théo Filippi as DJ's. Funkcast is a script to generate synchronized automatic music (from the weather fields) on 3D animations that has been of use to provide daily 84 forecasts to date.



*Figure 2.3: Weather funkcast, forecast with generative music*

Finally, we also developed FireCaster VR game, built with Unity game engine and in the frame of a Master Student project in order to dive into weather fields with a VR headset and hand controllers, render is much like the VR360 of 2.2 but interactive.

## Press and Media

In terms of media, wildfire simulation were, since 2012, the subject of recurrent interest from journalists and communication departments among which 3 Annual reports from research agencies (GENCI, ANR and CNRS), 5 Television occurrences ranging from 2 to 15 minutes (Arte Xenius, France 3, RTBF, France 2, France 3 Corse), 12 Scientific articles and pages in general public press (CNRS Journal, La Recherche, Le Monde, Ca M'intéresse, Nouvel Observateur, Météo et Climat info, Sapeurs-Pompiers de France Magazine) and 5 articles in regional press. I am also identified by the CNRS communication department as a reference wildfire scientist since 2014, providing selected interviews at any unfortunate times large wildfires make the news.



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# Scientific Production

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## Publications in international peer-reviewed journals

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Part II

Research activities

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# Discrete events simulation of environmental complex systems

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## Contents

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<b>4.1 Discrete events simulation of drifting seaweeds . . . . .</b>	<b>28</b>
4.1.1 DEVS Modelling methodology . . . . .	29
4.1.2 Lagrangian discrete event particle-tracking trajectory model . . . . .	31
<b>4.2 Specification of wildfire models and simulation framework . . . . .</b>	<b>33</b>
4.2.1 General description . . . . .	34
4.2.2 Specification formalism . . . . .	34
<b>4.3 Wildfire model representation and simulation evaluation . . . . .</b>	<b>37</b>
4.3.1 Representation and of a Fire Front and Notation . . . . .	37
4.3.2 Evaluation of wildfire simulation . . . . .	39
4.3.3 Model evaluation on large fire database . . . . .	41
<b>4.4 Conclusion . . . . .</b>	<b>43</b>

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Environmental system is used here as a general denomination for all systems that are in relation with nature, in particular we focus on understanding natural events and design system that help to plan or simulate the human response to a new environmental configuration. Such systems can span across different time and space scales (molecular to geological) and their complexity is often the consequence of multiple interactions between parts of systems occurring at those different scales. Among complex systems, a strong specificity of environmental ones is that they are spatially distributed. With the current computational and communication resources, it is now possible to perform simulation of such complex systems to understand observe and predict their dynamics. There is also a strong development in the availability of observational data and data collection methods, from satellites or sensors directly embedded in a studied environment.

The consequences of these technological advances is the increase in resolution and quality of the analysis and prediction of atmospheric and ocean models. But geophysical science is obviously not the sole beneficiary of these advances with ecologists and environmental behaviorists that may have a view of the system (and a way to specify it) that differs from ordinary differential equations and an Eulerian or Lagrangian field specification to solve them. Each of these paradigms is adapted from a view of the system, a view that can depend on the mental representation, knowledge and limitations of the modeler, implementation issues and availability of software. In particular there are different

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ways to handle time in different paradigms and environmental systems that also have the specificity to be coupled systems that are acting at different time scales and paces.

This chapter presents the effort to define a formal, coherent and generic framework for modeling and simulation of these environmental systems and takes its roots in Discrete Event modeling paradigm developed in my PhD (Filippi 2003a; Filippi and Bisgambiglia 2003). The first problem (section 4.1) that were to be handled was the simulation of drifting seaweeds (Komatsu et al. 2006; Filippi, Komatsu, and Tanaka 2010; Kokubu et al. 2019). Although it could have been simulated by developing a specific Lagrangian tracking code, a more generic approach was developed in order to be able to share this code with behavioral environmentalists. The developed approach made use of ocean current data as forcing data-sets, and opened the opportunity to work at the European Center for Medium Range Weather Forecast in Reading, UK. The work at ECMWF was focused on finding a solution to encode and decode efficiently and properly the enormous amount of geophysical data generated by the weather forecasting model and the creation of GRIB API (Grid in binary)(Filippi, Curic, et al. 2005) that evolved now in the library used by most weather forecasting models to encode simulation results. These two experiences did structure the computer engineering aspects for wildfire simulation (Filippi, Morandini, Balbi, and Hill 2009; Balbi et al. 2009b) developed when I entered CNRS at the SPE laboratory and presented in section 4.2. Once this framework was set, the obvious question was to qualify its performance in simulation (section 4.3), in the frame of my first PhD co-advising experience and the help of Inria Paris (Nader Hannah Milad 2015; Filippi, Mallet, and Nader 2014c; Filippi, Mallet, and Nader 2014b).

On this subject :

**Papers:** Komatsu et al. 2006; Filippi, Komatsu, and Tanaka 2010; Kokubu et al. 2019; Filippi and Bisgambiglia 2003; Filippi, Mallet, and Nader 2014c; Filippi, Mallet, and Nader 2014b; Filippi, Morandini, Balbi, and Hill 2009; Balbi et al. 2009b

**Book chapter :** Filippi, Komatsu, and Hill 2010

**These :** Nader Hannah Milad 2015

**Conferences :** 10 communications

### 4.1 Discrete events simulation of drifting seaweeds

This part is a summary of the article (Komatsu et al. 2006) entitled “Simulation of drifting seaweeds in East China Sea,” that uses data collection analysis performed in Komatsu et al. 2006. Simulation code is still in use, providing ongoing collaborations such as in Kokubu et al. 2019.

Drifting seaweeds plays a major role in areas where they are present. They act as nursery for a vast amount of species, but also are a good bio-indicator of water quality. Such algae host moving ecosystems, and identifying the drift path is necessary in order to clarify their roles. Particle tracking techniques have proven to be the most robust and common approach to identify drifting paths (Reynolds 2003). Mathematical models of particle tracking in the sea faces two main difficulties, the first is the lack of field data in order to evaluate the accuracy of such models. The second is the availability of ocean

current data representing seasonal variability. Trajectory and spreading models usually use resolutions of Lagrange particle tracking technique (García-Marténez and Flores-Tovar 1999), where particles simulate material transported by the water current, with various spreading mechanisms. The most common application of particle tracking spread models is the simulation of oil spills (García-Marténez and Flores-Tovar 1999; Bennett and Clites 1987).

Unlike oil spills models, drifting seaweeds has many aspects of interest. Such models applied to ecological science requires an advanced software framework to be build upon, because the simulation is not one of an inert particle, but of a living organism with a behavior that evolves in time and influences the drifting path. Model is to be observed by different point of views, with various variables that must be taken into account (biomass, distribution, mortality). These require the integration of several temporal, geographical and abstraction scales, therefore using a thoroughly engineered software architecture to match with the desired complexity and flexibility. We introduce here a discrete event approach for the simulation of these ecological systems. The JeoSim model consists of two subsystems. The first is a three-dimensional, sigma-coordinate hydrodynamic model, the Princeton Ocean Model, that calculates ocean velocity fields in the area of interest. The second subsystem is a Lagrangian particle tracking spreading model that calculates material trajectories using the results from the ocean circulation model.

The application presented here is the analysis and simulation of *Sargassum* Seagrass distribution in East China Sea to clarify ecological roles of this specie. Lots of drifting seaweeds are found in the East China Sea surrounded by Taiwan, China and Japan in spring. The Kuroshio Current passes northeasterly along the surface layer above 200m isobaths in the East China Sea. Tsushima Current is bifurcated southwest of Kyushu Island from the Kuroshio Current and enters the Japan Sea through Tsushima Strait. Origin of *Sargassum* species newly found as drifting seaweeds are thought to be geographically limited around Chinese coast in the East China Sea. *Sargassum* species were collected during on-site studies near Chinese coasts in East China Sea and Yellow Sea (Komatsu et al. 2006), and the zone further delimited with satellite imagery. Nevertheless, it is important to verify those assumptions with the use of simulation software to identify particle paths, distribution and the timing of the distribution. We will first describe how simulation has been formalized in a generic particle tracking solver called JeoSim, before presenting the simulation experiment in East China Sea.

#### 4.1.1 DEVS Modelling methodology

Jeosim is a tool designed for ecosystem modelers. Therefore, the user should focus only on modeling, while the associated simulation is generated automatically. To do so, it is important to base the separation between modeling and simulation on a strong formal basis. This ensures that the model can be verified analytically, and that the translation between the model and the simulation is mathematically correct.

The mathematical foundations of our discrete events approach lies in Systems Theory. The basics has been developed by Zeigler in the discrete event system specification (DEVS) formalism that can be found in Zeigler 1990. In this formalism, models are constructed in a modular and hierarchical manner. DEVS formalism is based on the use of two kinds of

models: basic and coupled. Basic models describe the behavior of basic system entities. Coupled models correspond to the structure and contain basic and coupled models as well as the link between them. Both basic and coupled models can be used as model components.

**DEVS formalism adapted to spatially explicit models**

The adapted method to suit spatially explicit models method consists in modeling each component of the studied system separately (Acquaviva, Filippi, and Bisgambiglia 2004). The system is represented with thematic layers communicating if necessary for the simulation. This is similar to the GIS representation of a system with several layers, each representing a specific point of view of the reality, and they are superposed to represent the whole system. With this representation, a specialist of each discipline involved in the study can work in his own field of knowledge and model a part of the system. In this approach, the models that are developed are just automatically coupled. It implies an efficient tasks distribution, a simplified reuse of existing models and a more targeted re engineering process, see Filippi and Bisgambiglia 2003 for details about the software. Figure 4.1 represents the Object Oriented Architecture of the Software. In the specific problem a particle derives from a GeoAtomic model, which is a model with spatial attributes. Each particle/geoatomic model is associated with a simulator and the coupled models that contain those Geoatoms also have data layers that drive the simulation.

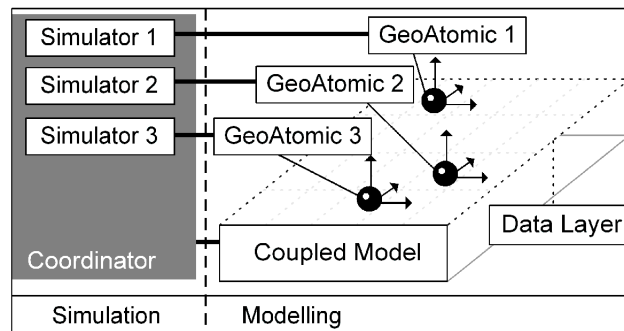


Figure 4.1: Architecture of the system

Thanks to the use of this formal base and the open architecture, JeoSim can be easily extended to include other biological processes that could occurs at different time and space scales. The next section presents in detail such adaptation for the case of the algae model.

**The DEVS *Sargassum* algae model**

A patch of algae is treated as a particle, that has a specific location, area and biomass. It has the following DEVS structure :

- X:**  $\{(p, v) | (p\{speed\}, v\{x - speed, y - speed, z - speed\})\}$
- Y:**  $\{(p, v) | (p\{position, status\}, v\{x, y, z\}\{attached, floating, sinking\})\}$
- S:**  $\{attached, floating, sinking\}, parameters\{x, y, z, biomass, area - size\} ,$



- $\delta_{int}$ :  $S \rightarrow S$  updates position, and move to the next sequential state if appropriate.
- $\mathbf{t}_a$ :  $S \rightarrow \mathbb{R}^+$  returns the time to next position update, or next state change,
- $\delta_{ext}$ :  $Q \times X \rightarrow S$  receives new speed information in case of position or state update,
- $\lambda$ :  $Q \times X \rightarrow S$  outputs new position and state.

#### 4.1.2 Lagrangian discrete event particle-tracking trajectory model

JeoSim calculates trajectories based on the assumption that behavior of drifting Seaweeds, like oils pills, can be idealized by numerous particles that moves in three dimensions in a water body by advection and spreading dynamics.

To determine the advective velocity field, JeoSim uses the 3D sigma coordinates Princeton Ocean Model (Mellor and Yamada 1982), that simulates ocean current, surface elevation, temperature, salinity and wind stress. The Princeton Ocean Model has been extensively tested and validated for the simulation of sea currents problems (POM 2005).

The velocities resulting from the hydrodynamic model is later used by the spread model to compute trajectories. The Lagrange particle tracking trajectory algorithm is based on the following vector equation:

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_a(\mathbf{x}_i, t) + \mathbf{v}_d(\mathbf{x}_i, t)$$

Where  $\mathbf{x}_i$  is the  $i$  particle coordinate,  $\mathbf{v}_a$  the advective velocity at the particle coordinate, and  $\mathbf{v}_d$  is the random velocity fluctuation. The hydrodynamic model determines the advective velocities at discrete times,  $t_n$  for  $n = 0..n$  and store it in a NetCDF (Unidata 2004) file for easy storing and analysis. To solve trajectories JeoSim uses an Euler method with trapezoidal approximation. In highly non-uniform flows, such as in oceans, this method stills imposes a strong constraint on time step to keep a good accuracy in zones of high speed currents. The way here to overcome these limitations by using discrete event simulation, is to have no fixed time step (or what can be called an adaptive time step), with calculation made instead for a step size  $\Delta q$ . Here  $n$  is an event index, and corresponds to an iteration with  $n = 0,1,2,3,..$  trajectories iterations indices. At each iteration, the time advance estimate,  $t_a$  is computed to be the time taken by the particle to travel the distance  $\Delta q$ .

With the trapezoidal rules, this gives the following implementation :

(step predictor)

$$t_a^* = \frac{\Delta q}{\mathbf{v}_a(\mathbf{x}_i^n, t)}$$

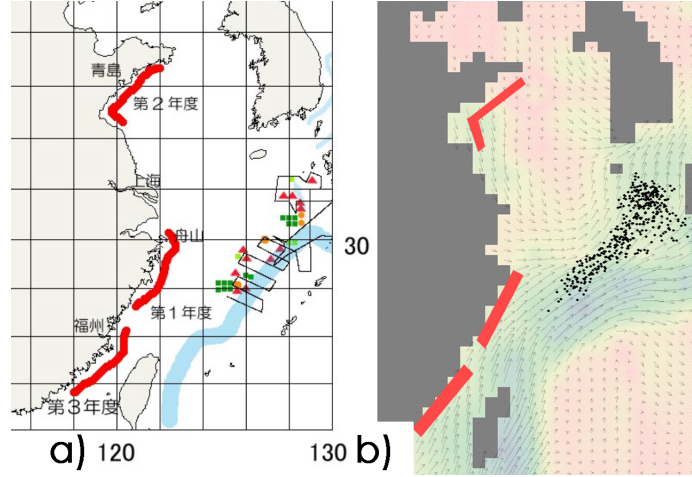
(predictor)

$$\mathbf{x}_i^{n+1*} = \mathbf{x}_i^n + t_a^*[\mathbf{v}_a(\mathbf{x}_i^n, t)]$$

(step estimate)

$$t_a = \frac{2\Delta q}{\mathbf{v}_a(\mathbf{x}_i^n, t^n) + \mathbf{v}_a(\mathbf{x}_i^{n+1*}, t+t_a)}$$

(corrector)



**Figure 4.2:** a) Distribution of drifting seaweeds in East China sea (circle squares and triangles maps to different *Sargassum* species). Red strokes corresponds to the supposed *Sargassum* origin, while the blue stroke represents the hot Kuroshio current flowing to the north-east. b) Particles dispersion in East China Sea (black dots), after 75 days of simulation using *JeoSIm* starting from March 15. Red strokes corresponds to the release zones.

$$\mathbf{x}_i^{n+1} \cong \mathbf{x}_i^n + \frac{t_a}{2} [\mathbf{v}_a(\mathbf{x}_i^n, t^n) + \mathbf{v}_a(\mathbf{x}_i^{n+1*}, t + t_a) + \mathbf{v}_d(\mathbf{x}_i^n, t) + \mathbf{v}_d(\mathbf{x}_i^{n+1*}, t + t_a)]$$

Random velocities  $\mathbf{v}_d$  are obtained by random sampling in the range of velocities  $[-U_r, U_r]$ ,  $[-V_r, V_r]$ ,  $[-W_r, W_r]$  to simulate spreading of seaweed patches. Those ranges are assumed to be proportional to diffusion coefficients in  $x$ ,  $y$  and  $z$ .

Velocities diffusion has been estimated from a study from Bograd et al. 1999, which uses satellites tracking of drifters in the northern Pacific to perform empirical estimates of diffusion coefficients. The relative diffusion coefficient is expressed by the following Formula:  $D_u = U_r/U(\text{rms})$  and  $D_v = V_r/V(\text{rms})$ . Bograd et al. 1999 found an average  $D_u$  to be 0.1 and  $D_v = 0.08$ . In the model,  $D_w = W_r/W(\text{rms})$  is given by the mortality and loss of floatability of the seaweed. Therefore, it is not assumed to have additional random motion, because the mortality distribution in itself is random.

### Application on Sargasso dispersion in East China Sea

In this section, *JeoSIm* is applied to predict *Sargasso* distribution in East China Sea. The aim of the simulation experiment is to have a better understanding of the *Sargasso* Path and validate the model and diffusion coefficients thanks to observation made onboard of the RV Hako-Maru (main research boat of the Ocean Research Institute) in March 2000. The Ocean Circulation simulation has been performed using the Princeton Ocean Model, a curvilinear sigma coordinates model that is very broadly used for ocean flow calculations. The grid is 150 cells wide, 80 high and has 20 levels. With a spacing of 34.4 minutes per cell along latitude and 27.75 along meridian on the grid.

The Laboratory of Behavior, Ecology and Observation Systems at the Ocean Research

Institute (University of Tokyo) filed observation in the East China Sea using R/V Hakuho-Maru. They mapped geographical distribution of drifting seaweeds and collected samples of drifting seaweeds to detect the species. Figure 4.2a) shows the distribution of *Sargassum* in the East China Sea (triangles, squares and circles) as found by the Laboratory in May 2002. Origin of *Sargassum* species newly found as drifting seaweeds are thought to be geographically limited around Chinese coast in the East China Sea. Figure 4.2b) presents the results of the simulation with a release date of 15 February, and a particle lifetime of 90 days. The numerical simulation using JeoSim provides results that prove to be very similar to the observation. In particular, it shows that the seaweeds are distributed on a path that is more north than the observation, which provides a good hint on where should be performed next observation.

The developed codes also allowed implementing different *Sargassum* behavior to serve new purposed such as recently to reveal evidence of their long-distance dispersal and seasonal aggregation to the deep sea by Yutaka Kokubu in 2019 (Kokubu et al. 2019).

After this work performed with behavioral ecologists, I had the chance to work in the data and services department at the European center for medium range weather forecast to develop the GRIB-API library (Filippi, Curic, et al. 2005) for a year, data quality and computational performance was my prime goal as a research engineer and developer. After ECMWF, I started as a full time researcher at the SPE laboratory, with a specific goal to develop simulation methods and framework to forecast wildfire using the wildfire physical models developed at the lab, the first task was to design a formal frame to these using the same approaches developed for *Sargassum* dispersion and also by the computer science team of the SPE lab. They are presented in the next section.

## 4.2 Specification of wildfire models and simulation framework

This section is a summary of Filippi, Morandini, Balbi, and Hill 2009 entitled that describes formalization a forest fire solver using DEVS formalism. After formalization, associated simulators have been designed to be used with a physical model in Balbi et al. 2009b and are the subject of chapter 5.

Simulation of moving interfaces, like a fire front usually requires the resolution of a large scale and detailed domain. Such computing needs to involve the use of supercomputers to process the large amount of data and calculations. This limitation is mainly due to the fact that large scale of space or time is usually split into node, cells or matrices, and consequently small time steps. This work presents a novel method that enables the simulation of large scale/high resolution systems by focusing on the interface, combining discrete event simulation (Zeigler 2000) and front tracking (Glimm et al. 1996; Risebro and Holden 2002).

Front tracking methods are used to study interface or boundary dynamics. By focusing on the boundary, it is possible to give a simplified view of a certain class of systems. The environment can be described differently because interfaces are stored as a set of points or vertices that does not have to be placed on a regular mesh or grid. The difference with regular meshes is that the entire map on which the system is evolving does not need to

be described in order to study its interface. The different points of the interface may also be placed on a continuous space, having real values for coordinates, a specific state of the system being a stable set of position in space.

### 4.2.1 General description

The phenomenon behavior is represented by a polygon, which is the discrete view of the continuous system front (Glimm et al. 1996). The polygon is decomposed into *geographic agents* that can either represents a point (crossing between segments) or the segment (the front line). If an agent is a point, then the shape is the polygon that is composed by the junction of all the agents. If an agent is a line, then the shape is recomposed by the crossing point of all lines. To move in space and time, each agent has a displacement vector and a reference position, that are state parameters. The interface evolves into an environment or a domain, that contains different area defined by polygons, each structural state change occurs anytime a collision happens between the interface and the environment, or the interface with an interface. Three kinds of collisions can occur :

**Internal collision** When there is an intersection of the interface the polygon with itself, it triggers a recomposition.

**Self-decomposition** Occurs if part of the interface has moved by a certain distance, or if the polygon has reached a critical size. The polygon interface triggers a decomposition by adding points, thus refining the shape.

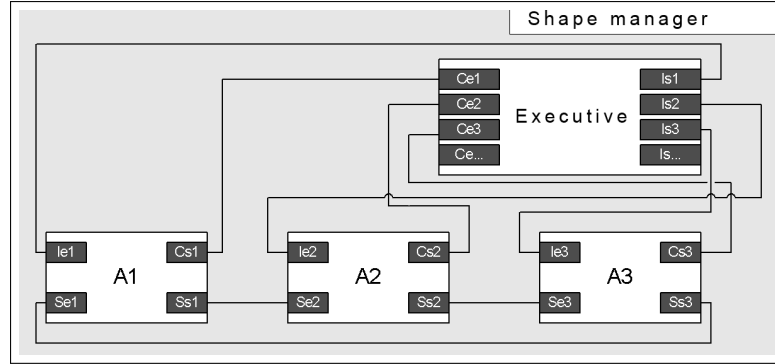
**External collision** occurs when the interface collides with an element of the environment or another interface. Decomposition is triggered and adapt the front to the new environment.

A few front tracking software packages exists that are used for the simulation of moving interfaces, most of them are problem specific (Glimm et al. 1996). In the case of discrete event front tracking, it is necessary to find a DEVS structure that will have the sufficient expressiveness to specify the most general models. Next section presents Vector-DEVS a formalization using DS-DEVS that can simplify the specification of dynamic interface models.

### 4.2.2 Specification formalism

DS-DEVS (Dynamic structure DEVS) formalism (Barros 1997) is used to specify models of front under a DEVS form. DS-DEVS allows the specification of variable and dynamic structure models that could be simulated in a discrete event fashion. Thanks to DS-DEVS, the front models inherits form the properties of DEVS model ; closure under coupling of DS-DEVS being proven in Barros 1997. DS-DEVS is used here to specify Vector-DEVS models that allow simpler definitions of models with dynamic front. Figure 4.3 presents the structural view of the internal couplings in a shape manager, the geographic agents  $A(1,2,3)$  are coupled by ports  $SE$  and  $SS$  and linked to the shape executive by ports  $Ie$  and  $Cs$ . These components have the following specifications:

the *Geographic agent*,  $A$ , is a basic DEVS model, representing either a point or a front of the borderline (a point or segment). A GeoAgent have a position and a displacement



**Figure 4.3:** Structural view of the internal coupling in a shape manager (light gray), Executive being the shape executive of the manager, models A(1,2,3) represents the geographic agents, dark gray squares the ports and the lines the internal coupling of the shape.

vector. The Agent can trigger the generation of new agent, as well as a position change. It has a similar structure as the agent 4.1.1 in section 4.1.

The *Shape manager* is a classical DS-DEVS network. It is a container for all agents in charge of activating and structure change. The structure is a set of connection between the agents that represents a polygonal shape. This structure is defined in the shape manager *executive*,  $\chi$ .

At initialization, the *Shape manager* generates the necessary agents to compose the original phenomenon border. The *Shape manager*  $SN$  of a shape  $N$  has the following structure :

$$SN_N = \langle X_N, Y_N, \chi, M_\chi \rangle \text{ with}$$

- $N$  Shape name,
- $X_N$  input set,
- $Y_N$  output set,
- $\chi$  shape executive,
- $M_\chi$  executive model  $\chi$ .

In this *Shape manager* the *executive*  $\chi$  is a spatial component that knows the structure as well as the structure dynamics.  $M_\chi$ , the executive model is a modified DEVS atomic model.

The *executive* links all agents; the set of links is defined in  $\sum$ .  $\chi$  contains the  $\gamma$  that defines the dynamics of the shape structure.  $\gamma$  triggers the creation, the linking and the destructions of agents.  $M_\chi$  is defined as :

$$M_\chi = \langle X_\chi(Ce1..Cen), S_\chi(TCs, E), Y_\chi(Is1..Isn), \\ \gamma, \sum^*, \delta_\chi, \lambda_\chi, ta_\chi \rangle$$

here,

- $X_\chi(Ce1..Cen)$  : is the input set from  $Ce1$  to  $Cen$  (figure 4.3) that listen for structural change messages,
- $S(TCs, E)$  : is the internal state and rules set containing :
  - $TCs(Dec, ADec)$  : structural change rule set (decomposition, self-decomposition),
  - $E$  : set of environment properties of the space that contains this shape.
- $Y_\chi(Is1..Isn)$  : is the output set from  $Is1$  to  $Isn$  that trigger message to the agent in case of an environment change  $\langle Ff\{Po(Ff)(x, y), Pd(Ff)(x, y)\} \rangle$  previously described.
- $\delta_\chi : \sum \rightarrow \sum$  : is the recomposition function that is triggered by internal collisions,
- $\lambda_\chi : S_\chi \rightarrow Y_\chi$  : output function that selects the neighboring frontiers that might collide with any of the shape's agents.
- $t_a\chi$  : time to next structural change resulting from a self-decomposition or a recomposition, return 0 in case of a collision triggered by an agent.
- $\gamma : S_\chi \rightarrow \sum^*$  : structure change function,
- $\sum^* \times TCs \rightarrow \sum^*$  : structure state set that is a result of a structure change.

A structure  $\sum_\alpha \in \sum^*$  and the associated states  $S_{\alpha, \chi} \in S_\chi$ , are given by :

$$\sum_\alpha = \gamma(s_{\alpha, \chi}) = (D_\alpha, \{M_{i, \alpha}\}, \{I_{i, \alpha}\}, \{Z_{i, \alpha}\}) \text{ where :}$$

- $D_\alpha$  : is the set of components associated with  $s_{\alpha, \chi}$ ,
- for all  $i \in D_\alpha$ ,  $M_{i, \alpha}$  is the DEVS atomic model of component  $i$ ,
- for all  $i \in D_\alpha \cup \{\chi, N\}$ ,  $\{I_{i, \alpha}\}$  is the set of components influencing  $i$ ,
- for all  $i \in D_\alpha \cup \{\chi\}$ ,  $\{Z_{i, \alpha}\}$  is the input function of component  $i$  and  $\{Z_{N, \alpha}\}$  is the output function.

The definition of Vector-DEVS models with the use of DS-DEVS formalism allows the specification of front models of discrete event evolutionary systems. This section presented a method formalized with DEVS paradigm to specify and perform simulation using fire rate of spread models. The next step is to describe, simulate and evaluate simulation of large wildfire. Some software already exist for the simulation of dynamic fronts, most of them using methods that are similar of front tracking method among which FARSITE, developed by Finney 1998, is probably the most used software in real scale forest fire simulation. Nevertheless, in FARSITE there are no formal notation or description of a wildfire available in order to develop quantitative methods that evaluate simulation results. The last part of the chapter is an attempt to provide such notation as well as a proposition of evaluation methods and simulation results with quantified performance.

### 4.3 Wildfire model representation and simulation evaluation

This section is a summary of papers entitled "Representation and evaluation of wildfire propagation simulations" (Filippi, Mallet, and Nader 2014a) and "Evaluation of forest fire models on a large observation database" (Filippi, Mallet, and Nader 2013) for a work developed in collaboration with Vivien Mallet from INRIA and the subject of PhD Candidate Bahaa Nader (Nader Hannah Milad 2015), co-advised with Professor Paul-Antoine Bisgambiglia.

Model evaluation usually requires comparing predicted to observed values and is critical to establish model's potential errors and credibility (Appel et al. 2011). Forest fire propagation models have been developed for over 60 years. Originally these models provided a scientific method to determine a propagation speed that could easily be compared with observed rate of spread. The comparison only involved simple statistics. With the availability of computer simulation, fire growth models became available and required new scoring methods. A few specific or widely recognized mathematical or statistical methods were developed to evaluate their results (Fujioka 2002). However, defining scoring methods for such models is not straightforward, as there exists a strong diversity in model's intents and scales, as well as diversity in available observations.

Depending on their purpose, the forest fire models have been built to predict either the stationary zero-dimensional propagation speed (Rothermel 1972) or the full fire front evolution over time (Finney 1998). Here we focus on models that can provide results at the scale at which the phenomenon is most usually observed (several hectares), e.g., Firestation (Lopes, Cruz, and Viegas 2002), Farsite (Finney 1998), ForeFire (Filippi, Morandini, Balbi, Hill, et al. 2009) and many others that may be found in Sullivan 2009c. It is important to note that using a scoring method will definitely not help to find the best model. All of these models have some kind of parameterization and are sensitive to the quality of input data (wind, fuel). This set of methods can help to better estimate these parameters when observation is available. Error methods are also required to estimate a confidence level in case of perturbed ensemble simulations or model ensemble simulations. Some reviews and investigations have been proposed for evaluation methods (Fujioka 2002), synthesized and extended in Finney 2000.

A formal mathematical representation of a wildfire is first provided, then a review of existing scoring methods using this formalism, proposition of new methods and a presentation of the associated tool that may be used to compute these scores. Using the proposed software, these methods are applied to synthetic simulation cases that are designed to expose methods strengths and weaknesses then model evaluation on a large case database.

#### 4.3.1 Representation and of a Fire Front and Notation

This section focuses on the mathematical representation of the state of a firespread model seen as a dynamic model. In addition to the model's state, other data is manipulated to carry out a wildfire simulation, such as elevation, fuel distribution, wind maps, but these data-sets are neither a direct observation of a wildfire or prognostic results of the simulation. Fuel evolution over time (burned, suppressed, water quantity), fire area and

surfaces are the typical data found in existing wildfire observation databases, even if available instruments does limit the quantity and quality of information that is available. After analyzing the French Promethee database, the European EFFIS database and fire reports, one can note that different information levels, types and formats can exist in forest fires data sources. A formal, mathematical representation of a forest fire must represent all this available information that can be divided into four levels.

For the simplest data, each event is composed of a time of occurrence, a scalar expressing the total area burned and an imprecise localization (a location name or reference index in a low resolution grid used by firefighters). For the second level, the data is composed of one or many accurate ignition points, an ignition date and the final burned surface in the form of a polygon. In the third level of data, it is possible to find timely information about the evolution of the fire front over time, essentially the global fire perimeter over time, but also the time at which fire has reached specific locations (like a road, a house, a ridge). Finally the most detailed data contains information about the actions performed by the firefighters and specific local information (flame height, intensity and spot-fire). Reports also often contain information about the wind, temperature and moisture evolution, but even if this information is important to simulate a wildfire, such information does not constitute a direct result of a wildfire propagation simulation to be evaluated.

Mathematical notation required to formalize scoring methods must be able to represent the most complex available information.

### Fire Representation

Let  $t$  be the time and  $X$  the spatial position. We introduce the fuel consumption  $\alpha(t, X)$  which is the ratio between the fuel mass available at  $t$  and position  $X$ , and the fuel mass initially available at  $X$ . It is set to 0 wherever no fuel has been burned yet, and to 1 where all the fuel has been consumed. At locations where the fire is active,  $\alpha(t, X)$  is between 0 and 1, depending on what proportion of fuel has been burned, relatively to the amount of fuel initially available. E.g.,  $\alpha(t, X)$  is 0.8 when 80% of the fuel initially available at  $X$  has been burned. Note that  $\alpha(t, X)$  may also be in  $]0, 1[$  at locations where the fire is not active anymore but did not burn all fuel. In locations where no fuel is available, no combustion can take place and  $\alpha(t, X)$  is set to 0, for any  $t$ .

The front  $\mathcal{F}(t)$  is defined as the closure of the region where the fuel is being burned at  $t$ :  $\mathcal{F}(t) = \overline{\{X | \dot{\alpha}(t, X) > 0\}}$  where  $\dot{\alpha}(t, X)$  is the time derivative of  $\alpha(t, X)$ . The burned area is defined as  $\mathcal{S}(t) = \overline{\{X | \alpha(t, X) > 0\}}$ . The first-arrival time of the front at  $X$  is set to  $+\infty$  if the front never reaches  $X$ , otherwise it is set to  $\mathcal{T}(X) = \inf\{t | \alpha(t, X) > 0\}$ .

We identify the observed values with the exponent  $o$ . For instance, the observed burned area at  $t$  is  $\mathcal{S}^o(t)$ .

### Model's State

In order to describe the full state of the model, the fuel consumption is needed as well as its time derivative that identifies the regions where the fire is active. The state of the system is thus defined as  $s(t, X) = (\alpha(t, X), \dot{\alpha}(t, X))$ .

We note  $|\mathcal{S}|$  the area of the surface  $\mathcal{S}$ . Using the Heaviside function  $H$ , defined so that



$H(x) = 0$  if  $x \leq 0$  and  $H(x) = 1$  if  $x > 0$ , we have  $|\mathcal{S}(t)| = \int H(\alpha(t, \cdot))$ . We denote  $\partial\mathcal{S}$  the boundary of  $\mathcal{S}$ , and  $|\partial\mathcal{S}|$  the length of the curve  $\partial\mathcal{S}$ .

We denote  $\Omega$  the complete domain of interest. We assume that  $\mathcal{S}(t), \mathcal{S}^o(t) \subset \Omega$  for any time  $t$ .

The simulation is run from  $t_0$  to  $t_f$ , and the observed fire is active from  $t_0^o$  to at most  $t_f^o$  where it was observed that the fire has stopped—note that the fire might have stopped earlier. Depending on the available information,  $t_f^o$  may not be available. The final simulation time used to carry out the simulation can be: (1) the time  $t_f^\times$  at which the simulated fire arrived to self-extinction – this is the only final time that can be used to forecast the final burned area, when observations are still unknown; (2) the time  $t_f^o$  when the final observation is taken; (3) the time  $t_f^{\bar{}}$  at which the area of the simulated fire equals the area of the observed burned surface; (4) the time  $t_f$  at which the simulated fire has the best agreement with the observations.

### 4.3.2 Evaluation of wildfire simulation

Visual comparison has traditionally been the main means of comparing observed and simulated fire patterns. It appears that it is more relevant to compare fire front shapes over time than comparing fields because the phenomenon is active only at the interface between burned and unburned fuel. Because of this specificity, most methods applied to forest fire evaluation come from the fields of image analysis and geospatial statistics. Among those, five were found to be employed to study forest fires.

**Sørensen similarity coefficient** (or Sørensen similarity index) is a statistical index, introduced in botany by Sørensen 1948. It computes the value (portion) of similarity between two samples. Perry, Sparrow, and Owens 1999 used this index to assess the agreement of fire simulation with observation.

**Jaccard similarity coefficient** Was originally developed by Jaccard 1901. It is a statistical index similar to the Sørensen index.

**Jaccard's index** Is also a straightforward comparison method. The value is defined as the area of the intersection divided by the area of the union of the two sample sets (simulated and observed burned surfaces).

**Kappa coefficients** Which are statistical measures of agreement, have been developed by Cohen 1960. It has gained widespread use in assessing model-simulated vegetation distribution (Duffenbaugh 2003). In the field of forest fire error, kappa statistics has been used by Arca et al. 2007 for the estimation of the error of the Farsite simulator (Finney 1998) in a Mediterranean area. It has also been used to compare and detect changes in vegetation maps (Monserud and Leemans 1992).

**Ratio of Areas** , This method is a ratio of selected areas between observed and simulated fire shapes. It was introduced by Fujioka 2002. It describes the accuracy of agreement between two raster maps. The ratio of the areas is the sum of ratios between observed and simulated burned sectors areas.

These methods may be automatically applied for relatively simple shapes (ellipses or convex shape) where a distance from the ignition point corresponds directly to a measure

of a front propagation distance. While this is usually true in constant fuel and topography conditions, this may not be the case with changing wind, complex terrain and heterogeneous fuels. Moreover, poor information about wind or ignition point might result in very similar, but rotated or translated shapes that may not necessarily represent a wrong behavior of the simulation model. Most of previous methods compare an observed fire to a simulated fire at the same time (i.e., the observation time) (Arca et al. 2007). This creates a large dependency of the error on the observation time, which is often not precisely evaluated—even the fire duration is uncertain as it lies between an estimated fire ignition and some time when the fire is “fully extinguished”. In particular, these methods are unable to identify a simulation that would have provided a good or bad fire shape at intermediate times.

Another approach would be to compare the full simulation to one observation at some time, taking into account every intermediate states/steps to provide a composite score. The arrival time agreement and shape agreement methods that we introduced in Filippi, Mallet, and Nader 2014a have been built to address these two issues. The first method is more suited to evaluate a simulation on a fully extinguished fire, while the second method may be more adapted to evaluate a running fire simulation.

Scores magnitude of one method cannot be compared with the magnitude of another method. Also it is generally not possible to identify a threshold (for scores) that would indicate that a simulation is reliable or not. Instead, for one scoring method, the score values should be compared to each other to determine which simulation is the best. In other words, it is hard to state whether a model better simulated one fire than another, but a scoring method should help to rank the simulations for a given fire.

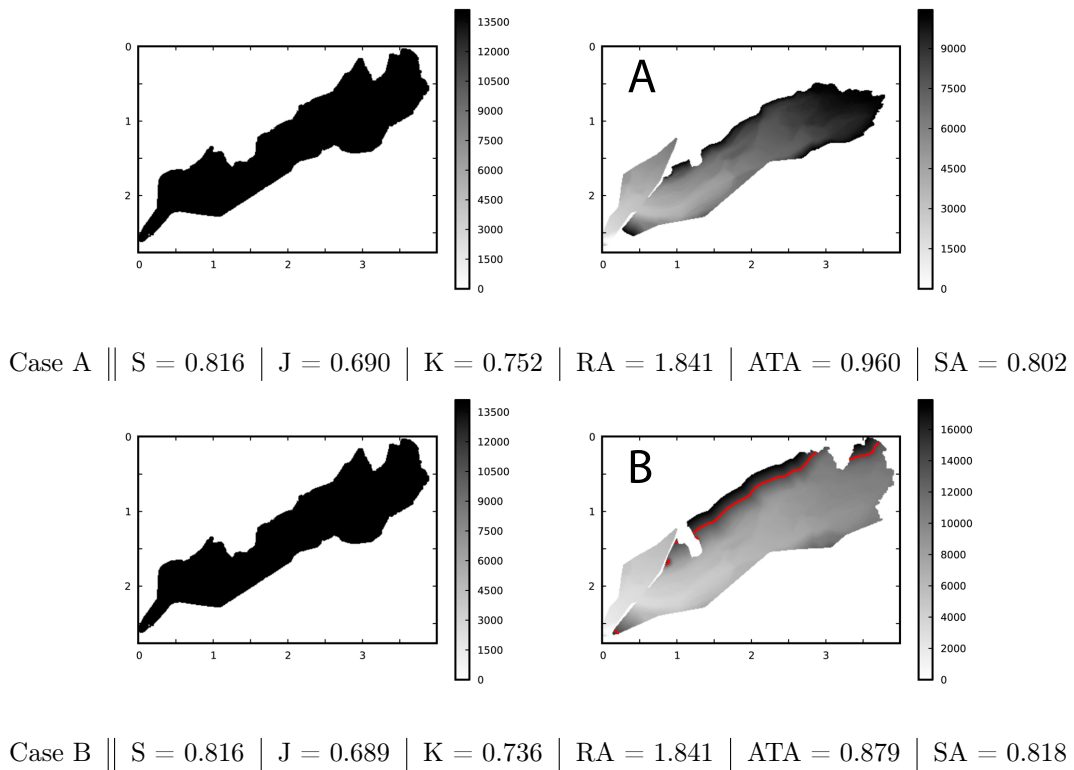
### Open source scoring code

The scoring methods have been implemented in a Python library with minimum dependencies. It is available at <http://sourceforge.net/projects/pyfirescore/>. It relies on NumPy (Oliphant 2006) and SciPy (Jones, Oliphant, Peterson, et al. 2001). The base format for forest fire simulation and observation is NetCDF, with a fire data convention such as proposed by Nader, Filippi, and Bisgambiglia 2011a. If the information is not directly available as a well formatted NetCDF file, it is possible to import data as bitmap image, points list or matrices in different file formats and encoding.

### Application on a real case example, Suartone Fire, 2003, SI456ha

The Suartone fire occurred in south-east Corsica on 28 July 2003 near the village of Suartone. About 456 ha were burned. The fire was detected at 15:00 local time. This fire first spread moderately in an area surrounded by shrubs before it jumped a road, shifting on its right flank. As this flank was about 350 – 400 m wide, it became the fire head and accelerated driven by both a  $8.3 \text{ m s}^{-1}$  western wind and upslope effect. Finally, fire suppression action were taken on both flanks of the fire to control it and the fire ended its spread toward the sea around 19:00 local time.

In this test, two simulations were run from  $t_0^o$  and with the same reference model, but until  $t_f = t_f^-$  (i.e., until the simulation has reached the same area as the final observed



**Figure 4.4:** Suartone fire: the fire burned 456 ha toward north east. The red line corresponds to the contour at time  $t_f^o$ . The grey scale represents the time in seconds, axes units are kilometers.

area) in case A, and until  $t_f = t_f^x$  in case B. The surface burned in case B is significantly larger than in case A. More details on the simulation settings for this case can be found in Santoni et al. 2011a.

Sørensen, Jaccard, and ratio of areas provide very similar, if not equal, scores in both cases because the impact on these scores of the overestimation in case B is equivalent to the impact of the underestimation in case A. Kappa coefficient gives a worse result for case B, because the overestimated area is relatively large compared to the domain size. Likewise, arrival time agreement strongly penalizes the overestimation in case B because the simulation burns significant areas long after the observed final time  $t_f^o$ . On the contrary, shape agreement clearly favors case B since it strongly penalizes the unburned area of case A after the early simulation end at  $t_f = t_f^-$ .

### 4.3.3 Model evaluation on large fire database

Model evaluation requires comparing predicted to observed values and is critical to establish model's potential errors and credibility. With the first step to evaluate model performance was to be able to evaluate single simulation results against observations, it is also important to know if a parameterization or a new formulation is superior, to continue the process of enhancing models, codes and data. A selection of 80 fire cases have been compiled into an observation database for this study. For each fire, the required initial data are pre-processed to generate the initial conditions and the data required by

the selected propagation model. The selection of the Corsica island was made because field expertise was available, as well as adequate data and homogeneity in fire dynamics given the relatively limited dataset (mostly shrubs and Mediterranean maquis). Fire sizes in the selection ranged from one hectare to several hundreds hectares, in order to be representative of all potential model uses.

### Four fire rate of spread models to rank

Fire propagation modeling can refer to a vast family of codes, formulations, systems or even data-sets (Sullivan 2009b; Sullivan 2009a). As this study focuses on the evaluation of large scale fire simulation, our selected definition of “fire model” is the formulation of the fire-front velocity. A velocity is obviously not enough to obtain fire progression and burned areas. A fire-front solver code and input data are needed. These two are the same for all models and described in the next section. Note that the proposed model selection is unfortunately not exhaustive of all existing formulations, but rather focuses on representing some kind of evolution in the model types.

Depending on their complexity, the models can take into account the terrain slope, the atmospheric properties (wind, temperature), fuels (mass loading, moisture content) and the fuel combustion properties. Each model prognoses the fire front velocity  $V$  in the normal direction to the front  $\vec{n}$ , pointing toward unburned fuel.

The first and most simple model makes the strong assumption that the fire is propagating at three percents of the wind velocity, as long as there is fuel available, regardless of the vegetation changes or the terrain slope. In practice, in order to compute the velocity everywhere on the fire front, the wind normal to the front  $W_s = \vec{v} \cdot \vec{n}$  is taken here as wind velocity, other three models tested are the Rothermel model (Rothermel 1972), the Balbi model (Balbi et al. 2009a) and the Balbi non-stationary model (Filippi and Balbi 2010).

### Simulation set-up

The 4 models were run using the simulation code formalized in 4.2 and further described in chapter 5, with 80 cases it resulted in a total of 320 simulations. Each simulation is set-up using the ignition point that defines where to carry out the simulation. The simulation domain is centered on the ignition point. In north-south and east-west directions, the domain size is about four times the extension of the fire. The spatial increment  $\delta l$  depends on the fire size. If the final observed burned area is  $A$ , then  $\delta l = \max(1, \log_{10} A - 4)m$ , if  $A$  is in  $m^2$ . The filtering distance  $d_f$  is set to  $20\delta l$ .

All simulations were carried out at most until the burned area equals the observed final burned area. In practice, on small fires, the area burned in the simulation may be larger because the stopping criterion is checked every 7 minutes (so the over-development cannot be more than 7 minutes of fire propagation). The simulation can also stop earlier if the front velocity is zero everywhere (stopped fire).

### Model Evaluation results

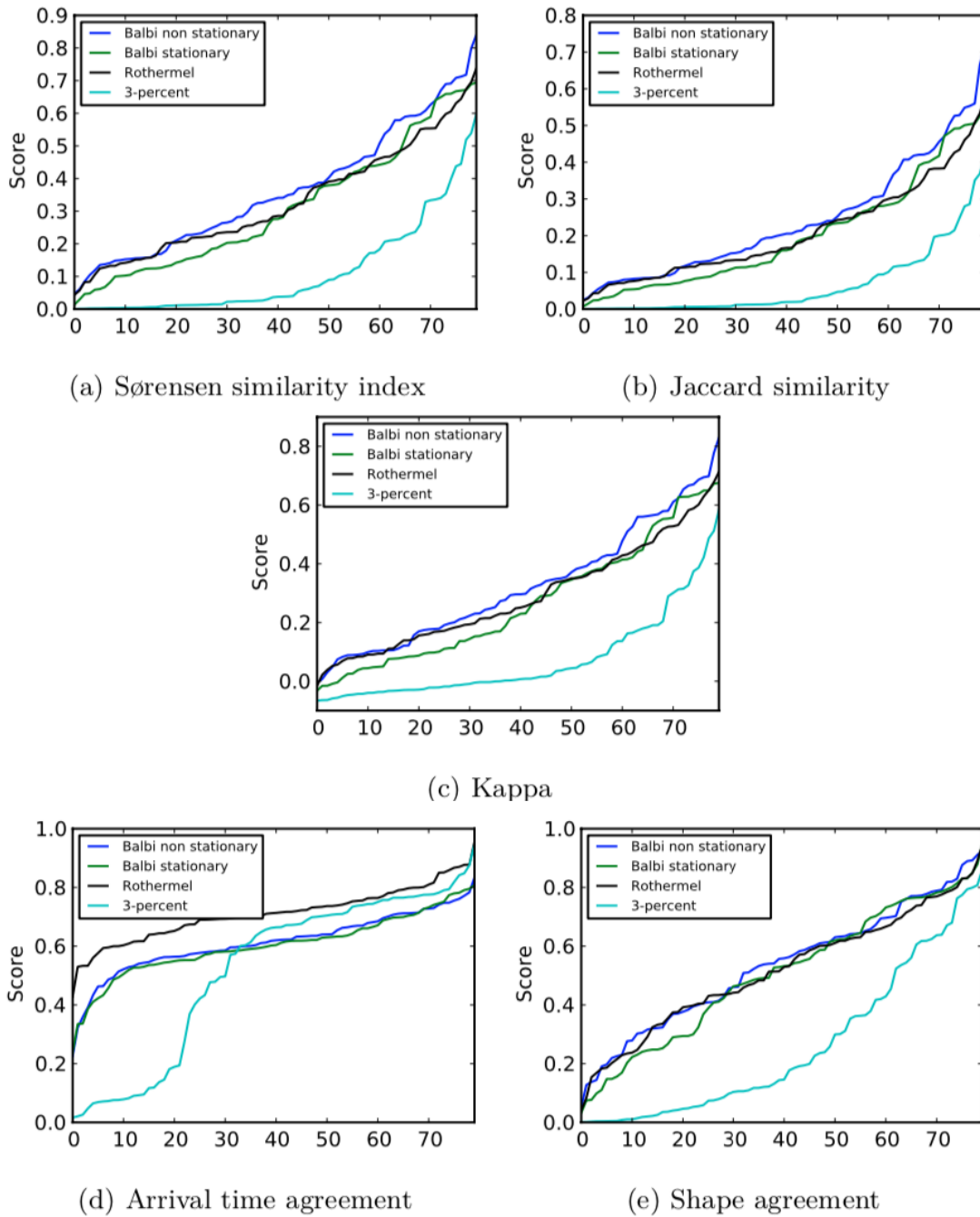
An important aspect of the comparison is to select and understand the way scores are presented. Let us consider the distribution of the 80 scores for each model and scoring

method. The 80 scores are here sorted in ascending order and plotted. It is important to note that the sorting is carried out independently for each model; so the number in the abscissae corresponds to a rank in the list of sorted simulations (per model), but not to the same fire case in all 4 distinct evaluated models. The figure 4.5 shows the distributions for all scoring methods. The distribution for the classical scores, Sørensen similarity index, Jaccard similarity coefficient and kappa coefficient, are very similar with worst score distributions for the 3-percent model. The Balbi models gives significantly better results. The Rothermel model arguably brings additional improvements over Balbi simulations for the lower scores in the distribution. The non-stationary Balbi model clearly provides the best overall results for this data-set. Less clear ranking is found with the distributions of shape agreements, Rothermel model is a clear first in the distributions of the arrival time agreements (figure 4.5d), with a close 3-percent model for the higher scores. We point out that all observed fires are assumed to last at most 24 hours (because no data for the duration of the fire were found), which is a very rough approximation to the actual duration of the fire. In these conditions, arrival time agreement is a less relevant scoring method than the other scores as it strongly penalizes over-prediction. Nevertheless it points out that the Rothermel model is less prone to over-prediction than all the other models. This is probably due to its wind limit function which slows down the front and is overall diffusive. Overall, one important analysis of these simulation results is that whatever model in use, scores can be high, but also do often rank low or null which is a clear marker that a major error source is not the model but initial and boundary condition that needs to be enhanced for consistent simulation results.

The analysis of scores obtained on idealized and real cases demonstrates some advantages of the dynamics-aware methods. However, it appears that no scoring method is able to perfectly synthesize a simulation error in a single number. The two proposed methods seem more appropriate if one wants to specifically evaluate the quality of the simulation dynamics. These methods can always be applied when the simulation arrival times or intermediate simulated fronts are recorded in the course of the simulation. In addition, these scores can be seamlessly applied with one final observed surface or with several intermediate observed burned surfaces. They always evaluate the whole simulation, from its ignition to its extinction.

## 4.4 Conclusion

This part presented most of the computer engineering research that has been set up in order to start developing a simulation framework for environmental models with an application to wildfire simulation. One of the main conclusion of these evaluations is that while the actual formulation of the model are important, there is definitely a strong influence of the quality of initial and boundary condition (landscape and meteorology) that must be taken into account in order to provide relevant forecasts. From this point forward, most of the research developments were focused on solving problems at the frontier of numerical simulation in meteorology, combustion and heat-transfer in vegetation.



**Figure 4.5:** The distribution of the scores for the 80 cases and for the 4 models. The sorting was carried out independently for each model.

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# Wildfire simulation and forecast

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## Contents

<b>5.1</b>	<b>Wildfire simulation</b>	<b>46</b>
5.1.1	Wildfire front velocity models	47
5.1.2	Front tracking the fire	50
5.1.3	Computation of front properties	56
5.1.4	Parallelization	60
5.1.5	ForeFire Open-Source Code and API	61
<b>5.2</b>	<b>Coupling fire and atmosphere</b>	<b>63</b>
5.2.1	Meso-NH atmospheric model	64
5.2.2	Coupling atmospheric and wildfire models	65
5.2.3	Validation on the FireFlux experiment	66
5.2.4	Simulation of large wildfire	73
5.2.5	Coupled Atmosphere/lava eruption	84
<b>5.3</b>	<b>Uncertainty quantification</b>	<b>87</b>
5.3.1	Generation of an ensemble of simulations	87
5.3.2	Calibration of an ensemble of simulations	88
5.3.3	Results of calibrated ensemble of simulations	89
<b>5.4</b>	<b>FireCaster wildfire forecasting system</b>	<b>91</b>
5.4.1	FireCaster and urgent computing context of fire forecasting	91
5.4.2	Daily forecast	92
5.4.3	Fire alert short-cast	93

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This chapter compiles most of the aspects of my current main research theme, wildfire simulation and forecast. The first section is the numerical method and code counterpart of the formal frame presented in the last section of the previous chapter (Filippi, Morandini, Balbi, and Hill 2009; Balbi et al. 2009b; Santoni et al. 2011b; Kaur et al. 2016; Zhang et al. 2017). This development is central to the whole research presented in this chapter as it is the code that is used thereafter to be coupled with an atmospheric model in the second section (Filippi, Bosseur, Mari, Lac, et al. 2009; Filippi et al. 2011b; Filippi, Pialat, and Clements 2013; Leroy-Cancellieri et al. 2014; Clements, Kochanski, et al. 2019; Strada et al. 2012b; Durand, Tulet, Leriche, Bielli, Villeneuve, Muro, et al. 2014; Durand 2016; Filippi, Bosseur, Mari, and Lac 2018; Lac et al. 2018), but also used to perform mass simulation and probabilistic fire risk estimates (Allaire, Mallet, and Filippi 2021; Allaire, Filippi, and Mallet 2020a) in the third section and finally as the core of a prototype fire

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weather forecasting system presented in the last section. Through all approaches, one of the main and maybe hardest problem was to develop, test and prototype methods and code using real data, cases and scenarios. Research presented here is therefore a trade off resulting of the use of a wide range of data quality, in-homogeneity, as well as expectations from both operational or research users. This theme is also the most representative of the collaborative work that I had the chance to lead, with a coordination of 3 national research program, first a CNRS funded exploratory research program followed by two funded by Agence Nationale de la Recherche (ANR) IDEA2.2 and FireCaster2.2 with larger consortium. More than financial support, developing such collaborative projects was what made this research possible with a well-defined structure of complementary laboratories and the opportunity it offered to co-advise two PhD students (Durand 2016; Allaire, Mallet, and Filippi 2021; Allaire, Filippi, and Mallet 2020a) and three Post-Doc researchers.

On this subject :

**Papers:** Filippi, Morandini, Balbi, and Hill 2009; Balbi et al. 2009b; Santoni et al. 2011b; Kaur et al. 2016; Zhang et al. 2017; Filippi, Bosseur, Mari, Lac, et al. 2009; Filippi et al. 2011b; Filippi, Pialat, and Clements 2013; Leroy-Cancellieri et al. 2014; Clements, Kochanski, et al. 2019; Filippi, Bosseur, Mari, and Lac 2018; Lac et al. 2018; Strada et al. 2012b; Durand, Tulet, Leriche, Bielli, Villeneuve, Muro, et al. 2014; Allaire, Mallet, and Filippi 2021; Allaire, Filippi, and Mallet 2020a

**Theses :** Durand 2016 and Frédéric Allaire in.prep.

**Conferences :** 14 communications

## 5.1 Wildfire simulation

Simulation of wildfire behavior can be useful in decision support systems in order to estimate how a wildfire will spread right after ignition and anticipate actions (Sullivan 2009c). The goal of such simulators is to provide the location of the fire front (along with several physical properties such as radiated heat) faster than real-time. In Chapter 4.2 we described the formal frame designed to simulate forest fire dynamics, this section provides details on the associated numerical methods and codes.

Numerous methods were developed in the past decades for the purpose of simulating interface dynamics in complex systems. Most popular methods (including Volume of Fluid, Level-Set and Front-Tracking)(Pitsch 2006) (PETERS 1999) use non-deformable eulerian grids for the velocity field which usually requires special treatment near the interface location. These methods can be divided into two categories, implicit (front-capturing) and explicit (front-tracking). Implicit methods reconstruct the interface from an additional field which grid is usually solved on the velocity field grid. So-called Volume of Fluid (VoF) schemes advects the volume fraction  $c$  of a reference material according to the velocity field and reconstruct an approximated interface in each mixed cell (cells where  $0 < c < 1$ ) according to geometrical and/or minimization process. Advection terms are enforced to preserve the mass in each material (Hirt and Nichols 1981; Rider and Kothe 1998). Level Set (LS) methods deals with the advection of the distance function from the



considered interface, and do not special treatment of advection terms the interface (Sussman, Smereka, and Osher 1994; Sethian 1996). Levelset methods usually provide more accurate interface geometrical properties (normal, curvature) than usual VoF methods but can fail in mass conservation. Explicit methods use markers to locate directly the interface (Risebro and Holden 2002). The interface is directly given by the locations of the tracked markers which gives a precise location and geometry of the interface. Such markers methods tends to be more complex to implement because of the additional computational geometry problems and are harder to parallelize as no straightforward domain decomposition can be done (Tryggvason et al. 2001).

In the scope of wildland fire spread with operational use, several of these methods were applied to capture/track the location of the fire front in time. As there is no mass conservation to enforce when capturing the interface, the most popular method is the level set method. It is in use in WRF-Fire (Patton and Coen 2004) and more recently WRF-SFIRE (Mandel, Beezley, and Kochanski 2011). One of the major drawback of these methods is the mesh resolution that can may be applied for large computational domains. A typical large Mediterranean wildland fire will spread over  $10^6 m^2$  requiring a computational domain in the order of  $10^6 m^2$ , while a 2 meter resolution is needed to take into account roads and fuel breaks that may have major impact on propagation dynamics. A regular grid for this domain would require around  $25 \cdot 10^6$  cells, which would greatly impact simulation time and memory usage. Moreover, estimating forecast uncertainties with an ensemble method would require simulating hundreds of such simulations in the same limited amount of time.

There are many ways to work around those limitations, increasing computer speed and memory, distributing calculus when it is possible, or optimizing the algorithms is a good way to enhance performance. Nevertheless, such large fires will develop in a few hours, and require a forecast that can be delivered in a few minutes in order to try different fire fighting scenarios. The goal of this work is to propose a method that is able to simulate in a few minutes the propagation of a large wildfire at a high resolution while keeping the ability to perform larger scale diagnostics in order to use this code coupled online with atmospheric dynamics models.

The physical model for the propagation velocity of the fire front is briefly presented first, before a focus on the “advection” scheme of the markers and how the topology is handled. Parallelization and diagnostic models are explained in the third subsection while some test cases investigating the numerical accuracy and efficiency of the proposed method are present in the fourth subsection. Last subsection presents the implementation before introducing the weather coupled application of the approach.

### 5.1.1 Wildfire front velocity models

This section illustrates the kind of models that can be solved by the proposed method and code. As the original purpose is forest fire simulation, it is focused mainly on explaining the topological approximation as well as presenting the most commonly used model and shortly present the formulation that has been introduced as default velocity function.

### The fire line approximation

Prediction of forest fire propagation is an active research topic since a few decades. One of the operational aim of the field is a fire spread simulator that can provide within minutes the most reachable and accurate prediction of the fire evolution. The balance between the accuracy of the fire model and the computational time has recently leaned towards the accuracy in favour of parallel computing; but a detailed treatment of the combustion processes involved in such large-scale phenomena is still not reachable as very detailed description of the fuel and fuel distribution would not be available over a large landscape. Simulation codes such as WFDS (Mell et al. 2007) or Firetec (Linn et al. 2002) requires the resolution of combustion processes at their characteristic scales, with billions of grid point and several hours of computational time for wildfire of the scale of 1 square kilometer. In these computational intensive code, the fire line and velocity is not what is explicitly computed, but is a diagnostic of the temperature of fuel consumption field. In the simplified approach that ForeFire code resolves, the lack of high resolution fields requires to have a prognostic formulation for the front velocity and simplifications of the combustion processes must therefore be made in order to solve fire front dynamics, such as the fire line approximation.

Based on the thinness of the fire front at the scale of large wildland fires, it implies three main hypothesis :

1. a fire front is considered as a fire line that separates unburned and burning areas, *i.e.* the flame properties such as geometry, temperature field, ... are modeled and attached to a line evolving on the earth's surface,
2. the propagation velocity  $\vec{R}$  is collinear with the front normal  $\vec{n}$  and its magnitude  $R$  is given (at each point of this line) by a velocity model depending on a set of inputs: the terrain slope angle normal to the front propagation  $\alpha$ , a set of vegetation (or fuel) properties  $\{\phi_i\}_{\text{fuel}}$ , a set of atmospheric conditions  $\{\phi_i\}_{\text{atmo}}$ , eventually a set fire front properties  $\{\phi_i\}_{\text{front}}$ :

$$\vec{R} = R(\alpha, \{\phi_i\}_{\text{fuel}}, \{\phi_i\}_{\text{atmo}}, \{\phi_i\}_{\text{front}})\vec{n}. \quad (5.1)$$

Wildfire front velocity models are a typical way of modeling the phenomenon for tools of operational uses, a non-exhaustive review of these formulations can be found in Sullivan 2009c and ranges from a widely used Rothermel model to the rule of thumb 10 percent model (Cruz et al. 2020). The ForeFire code comes with a version of these models readily available but is also intended to develop and test new formulation and adaptations of existing ones.

A particularity of ForeFire is the ability to develop such formulation using diagnostic variables of the local fire front state (local front depth and curvature). It enables to account for transient local front properties and allows developing models of non-stationary front velocity.

### A simplified physical model for the propagation velocity of wildland fire front

The purpose of this model is to illustrate what kind of velocity model can be solved by ForeFire and exposes typical parameters and state variables of use. A complete model

description and reduction from the mass and energy budgets around the flame is out of the topic of this paper but can be found in Balbi et al. 2009a and Filippi and Balbi 2010 as well as comparison with real fire incidents and error estimation in section 4.3. Only the synthetic equations governing the interface speed are presented here to illustrate the inclusion of local front properties in the equations and in the different sections of the section. The main simplifications of the model are based on these assumptions :

1. Flame section is assumed triangular with homogeneous temperature distribution  $T_f$ , with consequence that the volume/surface ratio of the flame ( $V/S$ ) depends on only the depth of the front  $\lambda$  and slope angle  $\gamma$  that represents the angle between the flame and the slope in the normal direction:

$$\frac{V}{S} = \frac{\lambda \cos \gamma}{2}, \quad (5.2)$$

2. The velocity in the flame  $\vec{u}$  is the geometric sum of wind velocity  $\vec{v}$  at mid-height of the flame (and supposed parallel to the ground) and the vertical velocity due to gas injection  $\vec{u}_i$ ,
3. The vegetation under the flame is considered homogeneous, at temperature  $T_v$ , with calorific capacity  $c_{p,v}$  and of constant thickness  $e_f$  larger than the optical length  $\delta_f$  of the vegetation (if  $e_f > \delta_f$ , *i.e.* all the of the radiation is absorbed by the vegetation),
4. Burning vegetation is considered at temperature of ignition  $T_i$ , and radiates towards the unburnt vegetation as a grey panel of emissivity  $\varepsilon_v$ ,
5. The actual ratio  $\chi$  of radiated energy over combustion heat release  $Q$  decreases from an optimal ratio  $\chi_0$  when the volume/surface ratio ( $V/S$ ) of the flame increases relative to an absorption efficiency  $\mu$ :  $\chi = \frac{\chi_0}{1 + \mu \frac{V}{S}}$ ,
6. The input air flow in the flame is assumed stoichiometric with proportion  $s$  and located in the bottom half of the flame. The degradation kinetic of the vegetation for the velocity model is also considered constant over time with duration  $\tau$ .

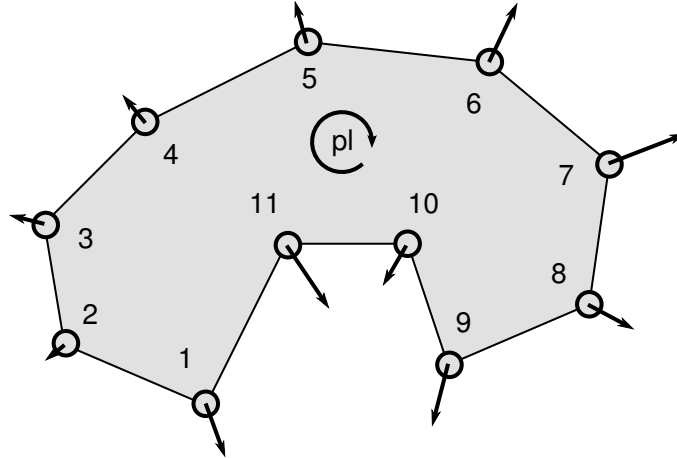
Using hypothesis 5 it is possible to estimate the portion of energy that participates for the propagation

$$\varepsilon_f B T_f^4 = \frac{\chi}{2} Q = \frac{\chi_0 \lambda \dot{\sigma} \Delta h}{2 + \mu \lambda \cos \gamma}. \quad (5.3)$$

Finally, the equation governing the propagation velocity of the front reads:

$$R = R_0(\varepsilon_v, T_i, e, \sigma, m, T_a) \left[ 1 + \frac{\chi_0 \Delta h \dot{\sigma}}{\varepsilon_v B T_i^4 e} f(\lambda, \kappa, \gamma) \right], \quad (5.4)$$

with  $R_0 = \varepsilon_v B T_i^4 e / 2\sigma [c_{p,v}(T_i - T_a) + m\Delta h_w]$  is the contribution of the burning vegetation, not influenced by the flame tilt angle or the front depth. This term can be interpreted as a conductive part and has generally low values. This is also the propagation velocity everywhere the flame isn't tilted towards the ground ( $\gamma < 0$ ), retrieving naturally the low



**Figure 5.1:** Example of a small fire front discretization with ordered markers.

values of backward fire fronts observed in every wildfire. To this conductive term is added a term that depends strongly on the geometry of the flame which is expressed by the mean of function  $f$ :

$$f(\lambda, \kappa, \gamma) = \frac{\lambda(1 + \sin \gamma - \cos \gamma)}{2 + \mu\lambda \cos \gamma} (1 + \kappa_f \sin \gamma) \mathcal{H}_{\mathbb{R}^+}(\gamma). \quad (5.5)$$

Where  $\kappa$  is the local curvature at the front position so that for a straight front there is no curvature effect or an acceleration in case of a convergence at the front location if the flame is tilted towards the unburnt.

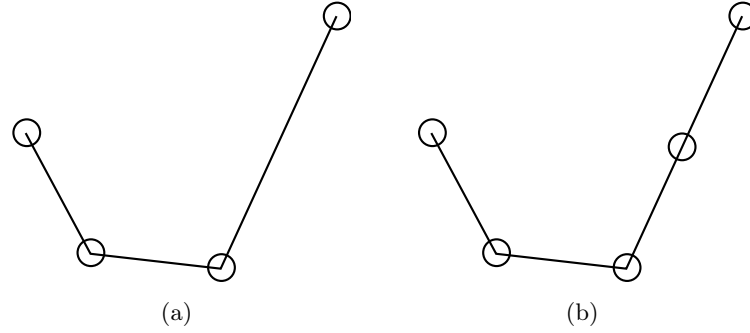
### 5.1.2 Front tracking the fire

#### Front topology

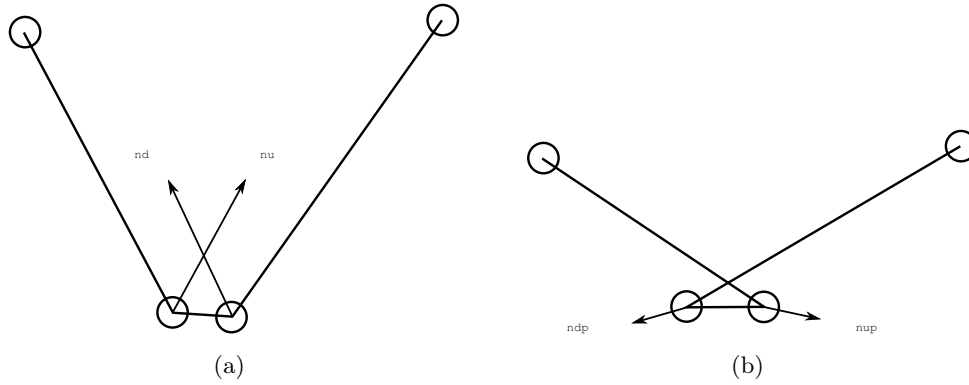
We consider the interface as a structured ordered list of  $n$  Lagrangian markers at locations  $\vec{x}_i$  on the earth's surface with  $1 \leq i \leq n$ . The interface is then tracked by advecting all these markers at the propagation velocity of the front, and by ensuring that the list of markers still holds an accurate representation of the interface. In this ordered list of markers, previous and next are defined by convention in the indirect direction as in figure 5.1. The outward normal defines the direction of propagation from burning regions towards unburned regions. Although fronts are allowed to contain islands of unburned fuel, they must remain simple polygons (with no self-intersection).

The appropriate level of accuracy of the discretization is specified through the maximum distance allowed between two consecutive markers, *i.e.* is the smallest spatial scale resolved along the fire front and is called the perimeter resolution. If two markers are farther than this distance, the resolution is degraded and a re-mapping of the front is performed to keep the resolution of the discretization under as in figure 5.2.

Front remapping is simply done by creating a new marker between the two surrounding



**Figure 5.2:** Minimal spatial resolution is kept by detecting markers that are farther than the perimeter resolution (a) and trigger a front remapping (b).



**Figure 5.3:** Two markers with location closer than  $d_f$  (a) may lead to self intersecting complex front (b).

markers:

$$\vec{x}^* = (\vec{x}_i^{(n)} + \vec{x}_{i+1}^{(n)})/2, \quad (5.6a)$$

$$t^* = (t_i^{(n)} + t_{i+1}^{(n)})/2. \quad (5.6b)$$

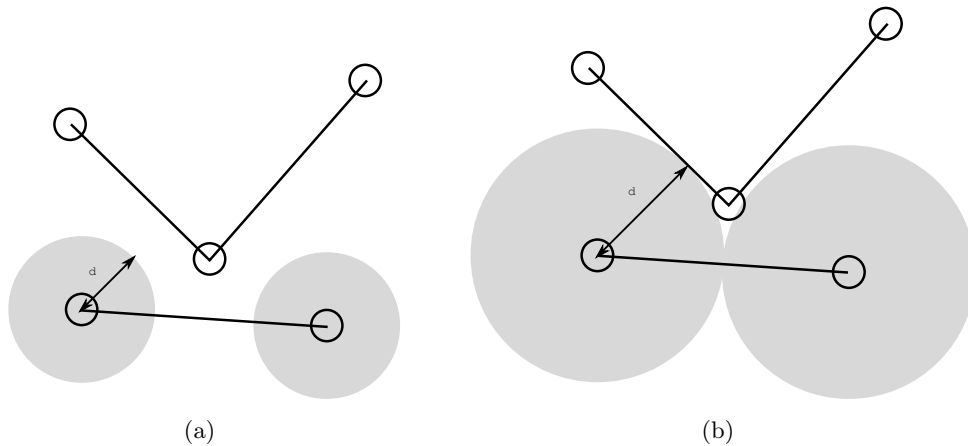
### Spatial filtering

Remapping is not only occurring when points are too far apart, but also too close. A filtering distance  $d_f$  is required to avoid self-intersections and keep a distance between points close to the distance.

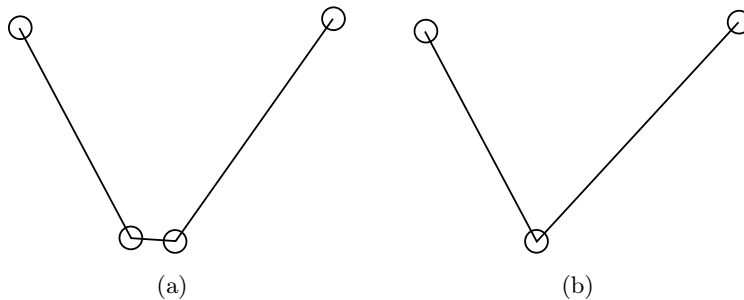
Spatial filtering is carried out at each marker movement to ensure that its location is far enough from every other node. The spatial distance of filtering  $d_f$  has to be at least larger than two times the spatial increment:

$$d_f > 2\delta l, \quad (5.7)$$

but may be several times higher than the spatial increment. Perimeter resolution and filtering distance are closely related by the need to accurately represent fronts merging or front portions. As can be seen from figure 5.4 a marker will be detected only if the



**Figure 5.4:** A filtering distance (area in grey) smaller than  $r/2$  may allow a marker to overlap a front without being detected (a). The condition  $d_f \geq r/2$  (b) allows detection.



**Figure 5.5:** When two consecutive markers have locations closer than  $d_f$  (a) one of them is removed (b).

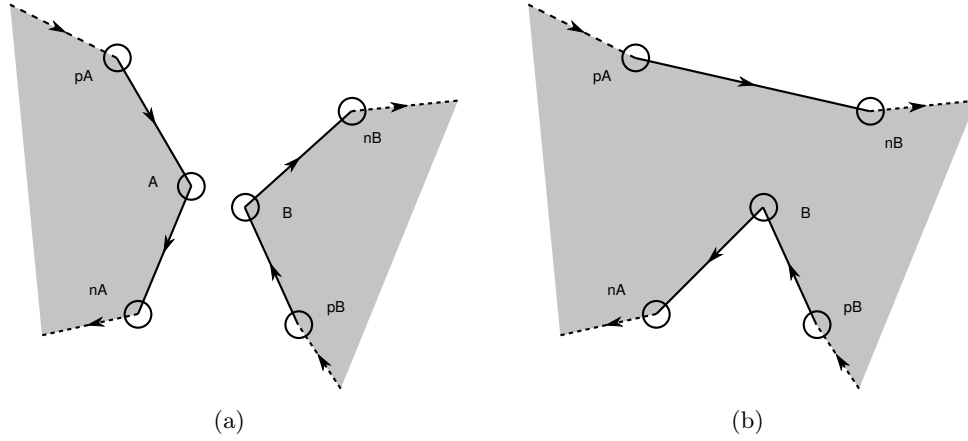
filtering distance is larger (or equal) to half the perimeter resolution. Moreover, this distance cannot be longer than the perimeter resolution so that  $r/2 \leq d_f < r$ . To make sure that the incoming marker merges with the closest marker a stronger relationship between the filtering distance and the perimeter resolution has to be set:

$$d_f = r/2. \quad (5.8)$$

Eventually front discretization is uniquely defined by the choice of a perimeter resolution and a spatial increment  $\delta l$  with the constraint, using eqs. (5.7) and (5.7), so that:  $2\delta l \leq d_f < r$  and  $r > 2d_f > 2\delta l$ .

The filtering process can take two forms depending on the two markers that are too close. If the markers are consecutive nodes in the front, the moving marker is removed from the front as in fig.5.5.

The situation is more complex when the two markers are not consecutive. When two front portions (from the same front or different ones) are colliding (see fig. 5.6) with a moving marker  $A$  detecting a close marker  $B$ . In this case, marker  $A$  is deleted, and the previous and the next markers are re-linked respectively with  $B$  and the previous marker of  $B$  to keep a valid topology.



**Figure 5.6:** Merging two portions of front (a). The previous marker  $A_p$  of colliding marker A is linked to the next marker  $B_n$  of the other colliding marker B. Marker B is linked to  $A_n$ , A is discarded (b).

If the front of collides with the another front, the two are merged. If the front collides with itself a new front is created inside the other. The new orientation of this inner front is naturally opposed to the orientation of the former front (see fig. 5.7) which allows accounting very easily for the phenomenon of inner front creation.

### Constant-CFL asynchronous advection of markers

The approach detailed below consists of a temporal scheme that allows to handle each marker at a time, recomputing a specific CFL constant local time step corresponding to  $\delta l$  and checking for topological changes.

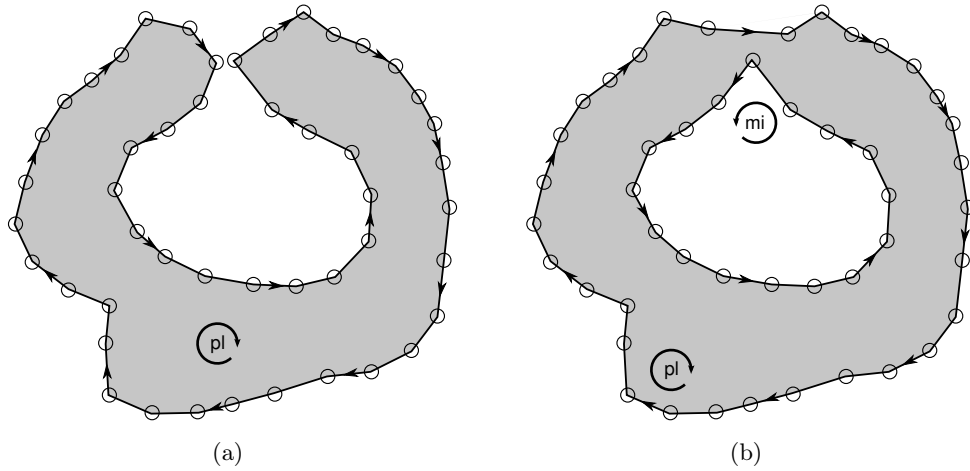
### Computing markers velocity

A set of local values  $\{\alpha, \{\phi_i\}_{\text{fuel}}, \{\phi_i\}_{\text{atmo}}, \{\phi_i\}_{\text{front}}\}$  must be retrieved to compute the velocity of each marker  $\vec{v}_i$  according to eq. (5.1). These properties are retrieved as follows:

1. Slope angle is computed from the difference in elevation between the current location of the marker and its projected future location (distance  $\delta l$  in the normal direction),
2. Fuel properties are taken at the current location and date of the marker,
3. Atmospheric wind is taken as a simple bilinear interpolation of the wind field at flame height, current location and date,
4. Front properties are computed at current location as described later.

### Timetable

A simple way to understand how the simulation is handled in the scheduler is to compare it with a standard time integration, here for a simple front composed of three markers. These markers have velocities spread over a few decades, with  $v_A = 10^{-2}m.s^{-1}$ ,  $v_B = 10^{-1}m.s^{-1}$  and  $v_C = 1m.s^{-1}$  (a spread that may be found in real fires with a strong wind pushing



**Figure 5.7:** Merging between two portions of the same front (a) results in the creation of an inner front (b).

head fire in a given direction). A time-step must be chosen for the discrete time integration approach, corresponding here to the spatial increment  $\delta l = 1m$  (our resolution) divided by the estimated maximum velocity of the simulation ( $CFL = 1$ ), *i.e.*  $dt = \delta l / 1 = 1s$ . Here  $3 \times 60 = 180$  marker updates are required to simulate the 60s of simulation, with as many checks to handle topological changes.

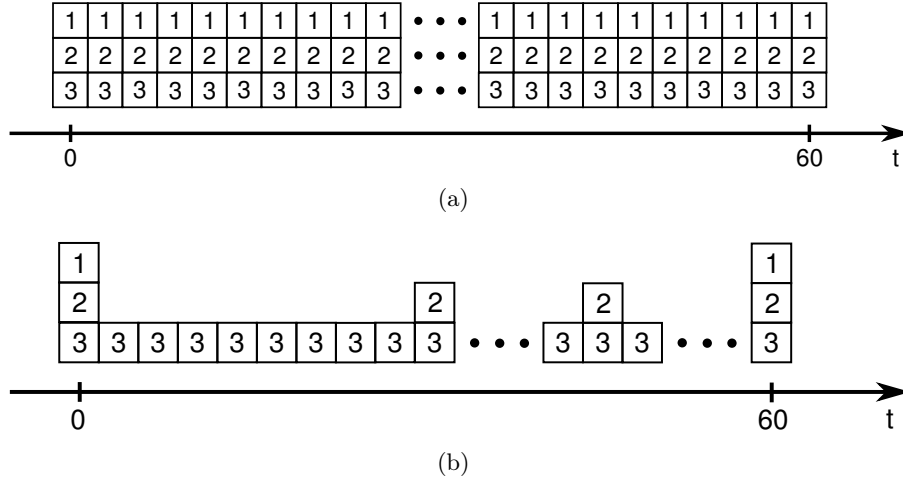
With a space integration approach, marker A is directly scheduled to reach its next position at  $dt_1 = \delta l / v_A = 100s$ , *i.e.* this marker has already reached its position at the end of a 60s simulation. Marker B is scheduled at over  $dt_{12} = \delta l / v_B = 10s$ , *i.e.* this marker will be updated 6 times before the end of the simulation. Finally, the fastest marker will have to be updated 60 times before the end of the simulation. Overall advection is solved 67 times to simulate the full 60s with as many topological checks around the marker, roughly three times less than with time integration. The comparison on the update events for each marker between the two simulation process is presented in 5.8. The counterpart of such feature is the necessity to keep track of update times for each marker in the sorted timetable (scheduler) that activates most imminent markers one at a time.

Scheduling can be seen as the most aggressive automatic time stepping method and requires a time-consuming and relatively complex data structure for time sorting but allows for constant CFL simulation. Aside from This timetable also handles all collision and simulation interaction events as the data structure required to take into account any scenario for change in fuel properties or any of the system's state runtime.

### Front history

The propagation velocity of the fire front given by eq. (5.4) depends on the flame geometrical properties: tilt angle, curvature and front depth. The two firsts properties are assumed instantaneous in the model and may be observed from the front geometry or computed at a given time. In the proposed method a high resolution matrix of arrival time is used to keep track of the fire history top perform instantaneous surface diagnostics.





**Figure 5.8:** Comparison of update events for each marker between time-integration (a) and space-integration (b) simulations.

### Computation of arrival time map

Arrival Time (AT) map is regular mesh on domain  $\mathcal{D}$  with size  $n_x^{\text{at}} \times n_y^{\text{at}}$  and resolution  $\delta_x^{\text{at}} \times \delta_y^{\text{at}}$  (which minimum  $\delta^{\text{at}}$  is called the arrival time map resolution). Each cell of the associated matrix stores the information of the first time the fire touches this cell, and is infinite when the fire has not reached the cell yet. To collect all the information on the fire dynamics the resolution of the map should be set so that each time a marker is moving this information can be stored. This results in condition that a marker spatial integration step  $\delta l$  cannot be larger than a map point:

$$\delta^{\text{at}} \leq \delta l / \sqrt{2}, \quad (5.9)$$

a condition typically met as a really high fire resolution is imposed even on very large domains.

This condition can be further mitigated by the hypothesis that a fire won't propagate if its depth is lower than  $d_e$ . Following the map of arrival times resolution is taken as:

$$\delta^{\text{at}} = \max(\delta l / \sqrt{2}, d_e). \quad (5.10)$$

### Fluxes models

Fluxes models are required to perform online diagnostics from the fire front behavior. Typically, these modes fluxes are usually used to diagnose heat flux  $\Phi_h$  and water vapor flux  $\Phi_w$  but may be complemented with other physical and/or chemical species fluxes as they can be easily added in the code. Such models are assumed to provide instantaneous fluxes values according to fuel properties and time since ignition (here the difference between the arrival time of the fire and the actual simulation time). Although a strong simplification, this may still be representative and a usual way to define such combustion models in wildfire (Burrows 2001; Anderson 1969).

A typical example of such simple flux model is a heat flux models that constantly releasing heat during a fuel dependent burning duration  $\tau$ . Let's denote by  $\Phi_h^t(\mathbf{x})$  the total heat released during the burning process at location  $\mathbf{x}$ , and  $\tau(\mathbf{x})$  the duration of the burning process. These constant release flux models is then be modeled as:

$$\Phi_h(\mathbf{x}, t) = \frac{\Phi_h^t(\mathbf{x})}{\tau(\mathbf{x})} \Pi_{[0, \tau(\mathbf{x})]}(t - t^a(\mathbf{x})) \quad (5.11)$$

with  $\Pi_{[0, \tau(\mathbf{x})]}$  the gate function on time interval  $[0, \tau(\mathbf{x})]$ .

### 5.1.3 Computation of front properties

Markers advection requires to compute the propagation velocity of the fire front at the marker's location. If external properties are forced from the initial data flame front geometrical properties front normal  $\vec{n}$ , depth  $\lambda$ , curvature  $\kappa$  and slope angle  $\gamma$  requires estimation.

#### front normal

The next marker position  $\vec{x}_i^{(n+1)} = \vec{x}_i^{(n)} + \delta l \vec{n}_i^{(n)}$  is computed immediately after marker update to its new position  $\vec{x}_i^{(n)}$ , requiring the approximation of the front normal. It is likely that the numerical scheme designed to estimate the unit vector normal to the fire front is of prime importance as it is central to the markers method. Three schemes were considered : medians, weighted medians and spline interpolation.

1. The standard median scheme compute approximations of the tangents in each segment on both sides of the marker:

$$\vec{t}_l = \frac{\vec{x}_i - \vec{x}_{i-1}}{|\vec{x}_i - \vec{x}_{i-1}|}, \quad (5.12a)$$

$$\vec{t}_r = \frac{\vec{x}_{i+1} - \vec{x}_i}{|\vec{x}_{i+1} - \vec{x}_i|}, \quad (5.12b)$$

with approximate tangent vector given by :

$$\vec{t} = \frac{1}{2}(\vec{t}_l + \vec{t}_r) \quad (5.13)$$

2. The weighted median scheme is similar to the standard median, but with an approximate tangent vector given by :

$$\vec{t} = \frac{d_l}{d_l + d_r} \vec{t}_l + \frac{d_r}{d_l + d_r} \vec{t}_r \quad (5.14)$$

with  $d_l$  the distance to the previous marker and  $d_r$  the distance to the next marker.

3. The spline scheme is a cubic spline interpolation of the front.

Convergence and precision of these different schemes are studied using norms based on the difference in angles between the approximated normals and the theoretical ones. Computed normals on all the  $n$  markers of the front are noted  $(\vec{n}_i)_{1 \leq i \leq n}$  and theoretical values  $(\vec{n}_i^{\text{th}})_{1 \leq i \leq n}$ . The  $\mathcal{L}^k$  norm is defined as:

$$\mathcal{L}^k(\vec{n}) = \frac{1}{n} \left( \sum_i \arccos(\vec{n}_i \cdot \vec{n}_i^{\text{th}})^k \right)^{1/k}, \quad (5.15)$$

and by extension  $\mathcal{L}^\infty(\vec{n}) = \max(\arccos(\vec{n}_i \cdot \vec{n}_i^{\text{th}}))$ .

Results of three schemes were similar in simplest case (circle), but a more representative test for a fireline is the discretization of a disturbed ellipsoidal front defined by the polar equation:

$$r(\theta) = \frac{a(1 - e^2)^{1/2}}{(1 - e^2 \cos^2(\theta))^{1/2}} + d \sin(k\theta), \quad (5.16)$$

with  $a$  and  $e$  the great axe and eccentricity of the ellipse,  $d$  and  $k$  the parameters of the disturbance.

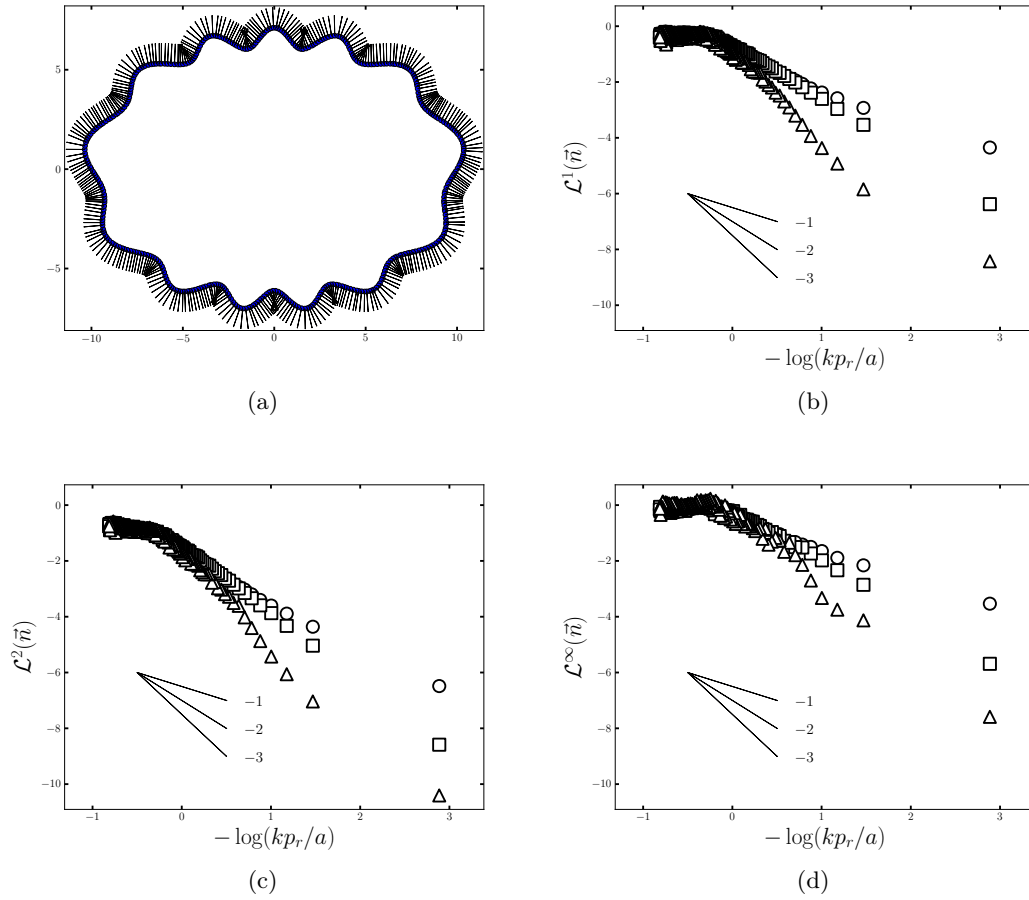
Figure 5.9(a) presents an example of the front discretization by markers (for perimeter resolution =  $0.1m$ ) with theoretical normals. Distances between markers  $d$  is randomly drawn to insure  $\sqrt{2} < d < 2$  so that the markers are not homogeneously distributed along the front as in real simulations. Convergence tests in 5.9(b,c,d) were considered with varying from  $10^{-3}m$  to  $5m$ .

Figure 5.9 presents the results concerning the most common norms  $\mathcal{L}^1$ ,  $\mathcal{L}^2$  and  $\mathcal{L}^\infty$  for what is considered a representative shape. Slopes for first, second and third order are also reported to have a direct estimation of the order of convergence of the scheme. As expected the spline interpolation performs better as far in terms of order of convergence with a convergence of order three, while the medians-based schemes exhibit first and second order convergence. Surprisingly the level of accuracy reached by the different schemes are very similar in a large range of the ratio  $k/a$ , *i.e.* for perimeter resolution included in  $[0.1a/k, 10a/k]$ . The ratio  $a/k$  is representative of the length scale of variation of the front, indicating that unevenly distributed markers deteriorate the performance of the higher order schemes, resulting in similar results approximately up to  $= 0.1a/k$ .

This feature is particularly relevant in the frame of faster-than-real-time simulation of large wildland fires. In such simulations it is very likely than the length scales range will be too wide to take into account ground details that will be finer than 0.1. The choice of the scheme for normals is thus determined by the computational cost instead of the accuracy of the scheme, favouring medians-based schemes with weighted medians used as default.

### Front curvature

The curvature of the front  $\kappa_i$  at the marker location has a major influence on the radiation term in E. (5.4), which is supposed to be the dominant term in the propagation dynamics of most surface fire models, and overall a diagnostic variable that can be of used to estimate heat transfer interaction due to the local front shape (Hilton et al. 2018). The same test as for the front normals has been applied, with two schemes considered,



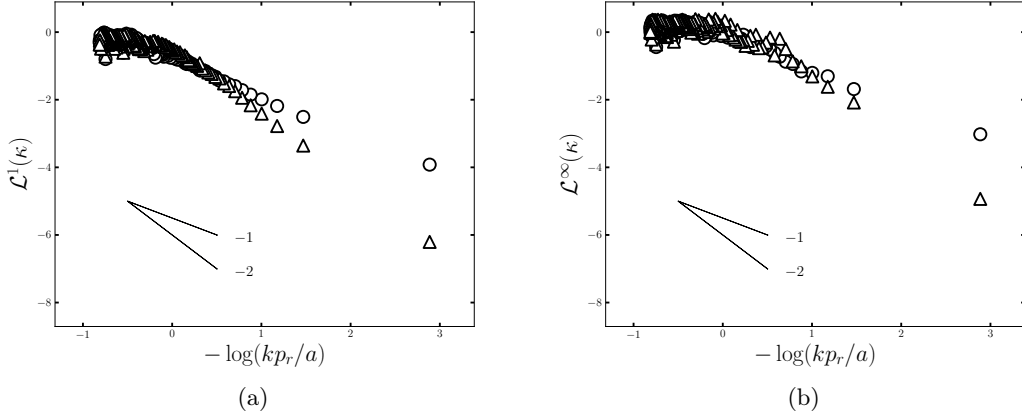
**Figure 5.9:** Comparison of the convergence of approximation of normals on a disturbed ellipsoidal front ( $a = 10$ ,  $e = 0.75$ ,  $d = 0.5$  and  $k = 13$ ) for several norms of the approximations following:  $\circ$ : medians,  $\square$ : weighted medians and  $\triangle$ : spline.

1. The first method computes the circumradius  $R_c(\vec{x}_{i-1}, \vec{x}_i, \vec{x}_{i+1})$  of the triangle composed by the marker and its two neighbors (preceding and following) with circumcenter easily computed as the intersection of the perpendicular bisectors of this triangle. Sign of the curvature is given by the sign of  $((\vec{x}_{i+1} - \vec{x}_i) \wedge (\vec{x}_i - \vec{x}_{i-1})) \cdot \vec{h}$ :

$$\kappa_i = \text{sign}(((\vec{x}_{i+1} - \vec{x}_i) \wedge (\vec{x}_i - \vec{x}_{i-1})) \cdot \vec{h}) / R_c(\vec{x}_{i-1}, \vec{x}_i, \vec{x}_{i+1}), \quad (5.17)$$

2. The second method approximates first and second-order derivatives in both directions ( $s_{,x}$ ,  $s_{,y}$ ,  $s_{,xx}$  and  $s_{,yy}$ ) according to a spline interpolation and computes curvature with the following formula:

$$\kappa = -\frac{s_{,x}s_{,yy} - s_{,y}s_{,xx}}{(s_{,x}^2 + s_{,y}^2)^{3/2}}. \quad (5.18)$$



**Figure 5.10:** Comparison of the convergence of approximation of curvatures on a disturbed ellipsoidal front ( $a = 10$ ,  $e = 0.75$ ,  $d = 0.5$  and  $k = 13$ ) for several norms following:  $\circ$ : circumcircle and  $\Delta$ : spline.

$\mathcal{L}^1$  and  $\mathcal{L}^\infty$  norms are given by:

$$\mathcal{L}^1(\kappa) = \frac{1}{n} \sum_i |\kappa_i - \kappa_i^{\text{th}}|, \quad (5.19a)$$

$$\mathcal{L}^\infty(\kappa) = \max(|\kappa_i - \kappa_i^{\text{th}}|). \quad (5.19b)$$

Figure 5.10 presents the curvature results for the same case study presented in Figure 5.9. Like in the previous test, Figure 5.10(a,b) shows slopes for first and second order with theoretical values for the order of convergence of the circumradius and splines schemes. These corroborates what was already observed for the normals, *i.e.* the non-uniform distribution of markers deteriorates the results of the scheme of higher order of convergence and accuracy in a large range of perimeter resolution are similar for all considered schemes.

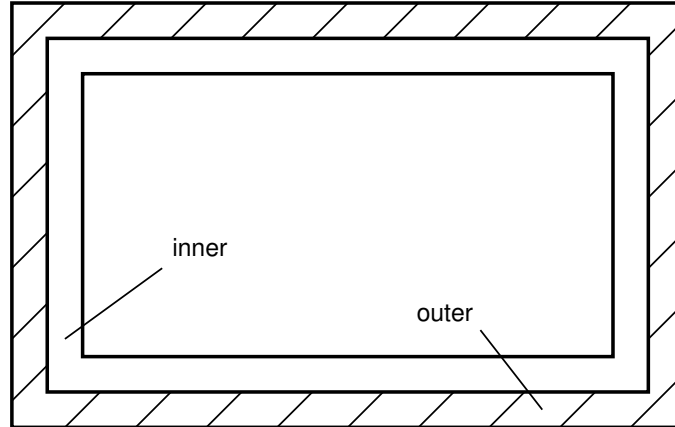
All scheme may be activated in the proposed implementation, but as these interpolations are extremely frequently called in a frame of a simulation, typical use of the code shown that using these first order trigonometric interpolation may divide by three the overall simulation time.

### Front depth

Similar to the curvature, the front depth (thickness of the flaming area) is an important property driving the propagation velocity of the targeted model and requires an estimation of the location of the rear front in the normal direction :

$$\vec{x}_r = \vec{x}_i - \lambda_i \vec{n}_i, \quad (5.20)$$

where it is checked whether the fire is still burning or not at this location. A flux model is required to determine if a location  $\vec{x}$  is flaming, and assumed if heat is above a specific threshold  $\Phi_h^{\text{ref}}$  typically set to  $1 \text{ Kw.m}^{-2}$ ] (about the maximum solar energy that may



**Figure 5.11:** Definition of the inner and outer halos for a sub-domain. The stripped domain is the where valid information comes from other processes.

be received a the ground). A constant heat release model is used in the typical set-up with a simplified model, that evenly spreads the fire available energy deduced from the combustion enthalpy  $\Delta h$  and fuel load  $\sigma$  during a burning duration  $\tau(\vec{x})$ . The model from (Anderson 1969) is used to deduce  $\tau(\vec{x})$  from the set of local fuel properties described in § 5.1.1. The location is then considered on fire if:

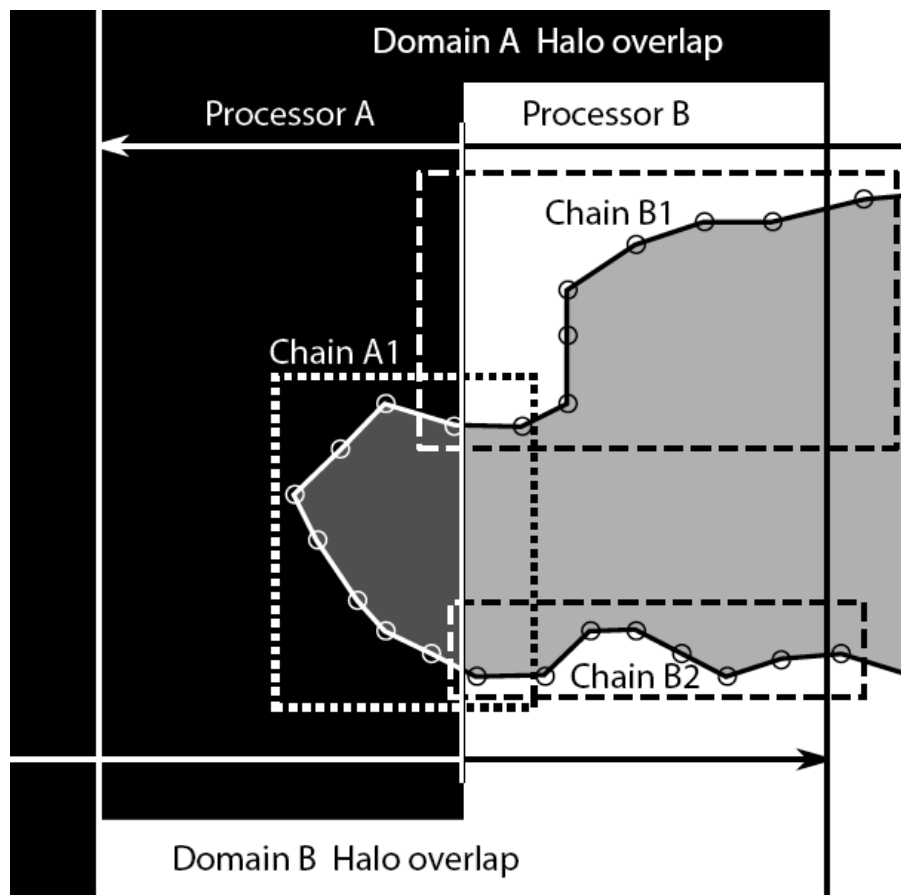
$$\Phi_h^{t_i - t^a(\vec{x}_i - \lambda_i \vec{n}_i)} > \Phi_h^{ref} \quad (5.21)$$

Where the arrival time  $t^a(\vec{x}_i - \lambda_i \vec{n}_i)$  is the time looked up on the map of arrival times (*cf.* § 5.1.2 and  $t_i$  is the current marker update time).

#### 5.1.4 Parallelization

The method was designed so that a fire-front computation can be made on a single computing core at a very high resolution. Nevertheless, such almost instantaneous speed might not be always possible in specific context, such as multiple fires spreading over a very large area, or in coupled fire-atmosphere simulation where the domain is already distributed over different processing units. The implemented parallelization strategies therefore mimics the one of atmospheric domains, each process is affected to the simulation of a sub-domain of the entire physical domain, with the specific task of keeping correct topology over a scattered front. Overlapping zones called halos (two or four cells large areas over each sub-domains boundary) handle communications between contiguous sub-domain with an inner halo (valid information that is sent) and outer halos (new valid information received) as in fig.5.11.

The distribution of markers information from halo to halo is performed with specific structures called “chains”(i.e. portions of fronts as in figure 5.12). Iterating over all markers, the first marker found in the inner halo is taken as a seed and a chain is then reconstructed as the list of all the markers connected to this seed and that are still in inner halo. This list is oriented, which means that the previous/next connections of the markers can be deduced from the order of appearance in the chain. Position, velocity, update time



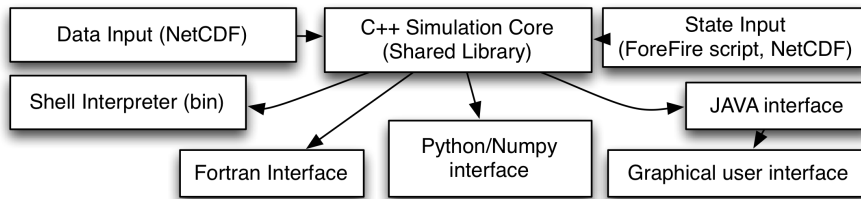
**Figure 5.12:** Communications of the state between process is made through the construction of chains of markers. Process A (simulating on domain A) gives the information of the markers inside the dotted perimeter (chain A1) (■ ■) to B, while B communicates the information about the two chains (B1, B2) surrounded by the dashed perimeter (---).

and identity for each marker are then passed through MPI processes at synchronous time steps (usually driven by the atmospheric model).

If the interface spread over more than two domains several processes will send the complementary chain information that must be merged together and prove to generate many unique topological configurations, all handled in the ForeFire Open-Source API.

### 5.1.5 ForeFire Open-Source Code and API

ForeFire is an expendable code that compiles into both an interpreter and a shared library. It has been designed so that it is easy to add and develop fire velocity and emission models, and easy to script or to interface it to other software for either physical coupling, model testing or develop specific user interfaces. For coupling purposes with other simulation codes, ForeFire is pure C/C++ and provides bindings to Java, C++, C and Python/Numpy and Fortran (figure 5.13), while a more operational or systematic use that can take the advantage of a specific simulation interpreter. Adding a velocity of fluxes model is simply done by adding a templated C++ file with only one function to define.



**Figure 5.13:** *ForeFire modules*

```

1 setParameters[propagationModel=Iso;Iso.speed=1]
2 FireDomain[sw=(-10.,-10.,0.);ne=(10.,10.,0.);t=0.]
3   FireFront[t=0.]
4     FireNode[loc=(-3,-3,0.);vel=(-0.5,-0.3,0.);t=0.]
5     FireNode[loc=(0.,3,0.);vel=(0.2,1.2,0.);t=0.]
6     FireNode[loc=(3,0.,0.);vel=(0.7,0.1,0.);t=0.]
7 step[dt=10s]
8 print[sim1.ff]
9 clear[]
10 include[sim1.ff]
11 step[dt=5.2s]
12 quit[]
  
```

**Figure 5.14:** *ForeFire scripting syntax*

### Command interaction

Forefire solver can be used once compiled using a command interpreter, which is the only application that result of compiling the package and a key aspect of any operational use. The interpreter binds with functions available in the library and offers a way to interact with the package with a simple, specific, scripting language so it is not compulsory to write and compile a C program to perform a simulation. Although it can be run in an interactive mode, a typical use of the interpreter would be to run it with a script file that already contains the instructions to perform the selected simulation and saves outputs. Being very application specific, the Forefire language is simple, there are no loops or conditionals, a script is meant to be the single flow of instructions of a single simulation scenario. Instruction set are sorted in four categories, parameters, geometry, actions and system. Moreover, as a simulation is event driven, each of the commands can be scheduled to be executed at a certain simulation date by post fixing a [t=date], and is the way potential modification of surface fuel moisture or fuel loading can be applied to simulation at a certain date to account for a fire fighting scenario.

### Sample use Case: simple simulation in Python

The originality of the code is its ability to be used in a variety of contexts, so the same developments (on a flux or velocity model, dataset, algorithm...) may be used to be tested in a pure analytic research mode, make its way to operations, and be compared easily with other approaches available from the same code. Python / Numpy bindings have been built to help C++ model development in a scientific environment (figure 5.15), with



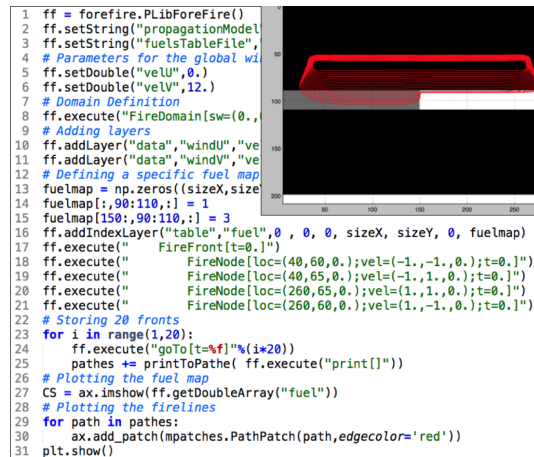


Figure 5.15: Sample python ideal fire propagation and graphical output

simulations that can benefit from all other Python bindings.

Built also with Fortran bindings as well as the ability to work in physical domains distributed on several processors, next section presents details of ForeFire uses coupled with the Meso-NH atmospheric model.

## 5.2 Coupling fire and atmosphere

This theme of research started in 2009 with prototype codes that were developed to estimate the ability, required parameterizations and resolutions for coupled fire-atmosphere simulation (Filippi, Bosseur, Mari, Lac, et al. 2009) developed in a CNRS funded exploratory program that I had the chance to coordinate. Interesting results motivated the development of the larger IDEA (Incendies de forêts, de la combustion aux émissions atmosphériques) program funded by Agence Nationale de la Recherche. The revised consolidated code was first validated on small scale but open air burning experiment in 2010 (Leroy-Cancellieri et al. 2014), then on the larger scale FireFlux experiment in Filippi, Pialat, and Clements 2013 and finally on large wildfire incident in Filippi, Bosseur, Mari, and Lac 2018. This section is mainly composed by an extended summary composed by these two last references and concludes by an extension of the fire coupling to lava-atmosphere work performed by co-advising the PhD of Jonathan Durand Durand, Tulet, Leriche, Bielli, Villeneuve, Muro, et al. 2014.

A large number of tightly coupled physical phenomena interact in the development of a large wildfire. Temperature increase in the fuel generates pyrolysis gases whose composition depends on the vegetation, and which can blaze. The intense heat release can modify dramatically the local meteorology, generating strong local convective motion and fire-induced winds, that in return modify the fire front dynamic and drive the fire propagation (Sun, Krueger, et al. 2009). To simulate wildfire, the fire front propagation must be solved at the scale of a few meters to precisely take into account wind, slope, humidity and obstacles (road, rocks). Eventually, fire-atmosphere interactions with the local motions need to be taken into account to properly represent the composition, density,

structure and transport of the plume.

Nevertheless, simulating large wildfires requires choosing between the accuracy of the code, data availability, the speed at which the result must be obtained and the computational framework. The variety of models thus ranges from physically detailed, fire/atmosphere coupled and computationally intensive (and limited to relatively small fires) models such as FIRETEC (Linn et al. 2002), WFDS (Mell et al. 2007) or FIRESTAR (Morvan 2001; Morvan 2004) to empirical, uncoupled (forced wind field) models such as FARSITE (Finney 1998) that are adapted to provide rapid simulation of very large wildfires. As an intermediate trade-off, approaches coupling 2D-surface fire propagation model with mesoscale atmospheric model (Clark et al. 1996a; Mandel, Beezley, and Kochanski 2011; Filippi et al. 2011a) have shown their ability to capture some complex phenomena occurring in large fires while still being adapted to real-time response.

This last approach is developed in this study that focuses on testing the ability of these coupled fire-atmosphere models to represent micro-scale atmospheric and fire front effects on a real and large observed fire case. Numerical fire/atmosphere coupling has already undergone numerous studies, starting from the static fire simulations of (Heilman and Fast 1992) to the pioneering works of (Clark et al. 1996a; Clark et al. 1996b) where a simplified model of (Rothermel 1972) fire spread is coupled to the atmospheric model of (Clark, Coen, and Latham 2004). More recently, the original Clark/Coen model evolved to the CAWFE model (Coen 2013), while efforts at extending the WRF Weather forecasting model (Skamarock and Klemp 2008) has resulted in the WRF/Fire module (Mandel, Beezley, and Kochanski 2011), widely used (e.g., Coen, Cameron, et al. 2013; Peace et al. 2016), even at the scale of large fires (several square kilometers (Kochanski, Jenkins, Mandel, et al. 2013) (Coen 2005)).

A similar system is used here, based on the atmospheric Meso-NH model (Lafore, Lac, et al. 2015; Lac et al. 2018) interactively coupled with the ForeFire firespread model presented in 5.

After a presentation of the models and code in the first subsection, a validation and simulation results on a large experimental and well instrumented burn are exposed in the second subsection, these helped to evaluate the sensitivity of the coupled code for larger scale simulation. The target large scale study presented in the third part is more ambitious with four large nested domains from 2.4 km to 50 m resolution, allowing to explore the local to the regional impact of a large wildfire in an interactive fire-atmosphere coupling. Fire front is integrated at the scale of thermal transfer (sub-meter), fuel consumption at the resolution of the vegetation database (5 m), local atmosphere and winds at the resolution of the convective structures above the fire front (50 meters) and continental smoke tracer transport at meso-scale resolution (over 2 km). Last subsection present an application of the coupled approach to lava/weather simulation.

### 5.2.1 Meso-NH atmospheric model

Meso-NH is an anelastic non hydrostatic mesoscale model (Lafore, Stein, et al. 1999), intended to be applicable to all scales ranging from large ( $\sim 1000m$ ) to small scales ( $\sim 10m$ ) and can be coupled with an on-line atmospheric chemistry module (Tulet, Crassier, et al. 2003). A joint effort of the Centre National de Recherche Météorologique and

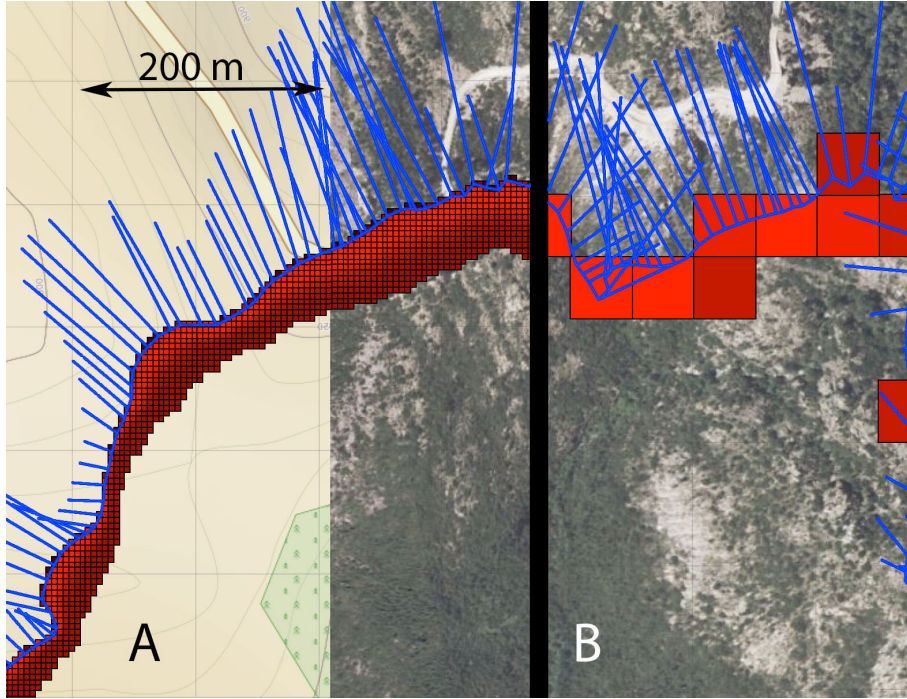
Laboratoire d'Aérodynamique. It comprises several elements; a numerical model able to simulate the atmospheric motions, ranging from the large meso-alpha scale down to the micro-scale. Primary meteorological variables (pressure, velocity and temperature) are advected with a centered 4<sup>th</sup> order scheme, while scalars and other meteorological variables (such as water vapor fraction) are advected with a so-called monotonic Piecewise Parabolic Method (Colella and Woodward 1984). Temporal derivatives are computed following the so-called leapfrog algorithm.

In this study Meso-NH is run in Large Eddy Simulation configuration as the typical size of the structures stemming from the fire forcing is typically several hundreds of meters. Due to the lack of chemical observations, and the computational cost of simulating chemistry ( $\sim 500\%$  augmentation), the authors chose to overlook the chemical issues and focus on the effects of the fire forcing on the atmospheric flow in the lowest layers.

### 5.2.2 Coupling atmospheric and wildfire models

Forcing of the atmosphere on the fire behavior is performed by estimating the atmospheric wind at mid-flame height at each markers location and at each atmospheric time-step. We use a bi-linear interpolation in space and time with the ground wind issued by the atmospheric model. Forcing the atmospheric model with ground conditions stemming from the fire is somewhat more difficult but elegant as Meso-NH is able to treat fluxes at ground level. As a meso-scale atmospheric model there is a clear limitation to the level of the combustion process that can be resolved. The atmospheric model is not designed for cells smaller than a few meters and the combustion model is therefore handled as a subgrid process, unlike other codes such as WFDS or FIRETEC. Despite these limitations, using a meso-scale atmospheric model is mandatory such as MesoNH to simulate large wildfires (that can extend several tens of kilometers) as more refined models cannot handle such large domains. The forcing mechanisms imposed by the fire on the atmosphere are then treated as ground fluxes to the atmospheric simulation.

Relevant forcing mechanisms are limited here to the ones usually considered in the literature (Kochanski, Jenkins, Krueger, et al. 2011) *i.e.* heat and water vapor fluxes. The modeling of these fluxes can be tricky as they should represent several physical phenomena such as vegetation drying by radiation, pyrolysis and soot production by combustion. All these effects are modeled within ForeFire to provide the best boundary conditions to the atmospheric model.



**Figure 5.16:** Typical simulation where fire markers (blue) and heat fluxes above  $30 \text{ kW m}^{-2}$  at fire resolution (5 m) (a) used to force the atmospheric surface fields (resolution 50 m) (a).

Computation of the desired fluxes is carried out using fluxes model defined in 5.1.1. Burning area is determined at each atmospheric time step and for each ground atmospheric cell as the difference between current time  $t$  and arrival time of the fire at the location  $t^a(\mathbf{x})$ . Figure 5.16A presents the typical upscaling required for this integration, with the markers building a high resolution arrival time matrix on which is applied a flux model  $\Phi$  on all the burning map cells  $\mathcal{I}_c$  contained in an atmospheric cell (fig5.16B).

Flux models for heat  $\Phi_h$  and water  $\Phi_w$  were defined as a constant release during a flaming duration  $\tau$ :

$$\Phi_h(\mathbf{x}, t) = \frac{\Phi_h^t}{\tau} \Pi_{[0,1]}\left(\frac{t - t^a(\mathbf{x})}{\tau}\right), \quad (5.22a)$$

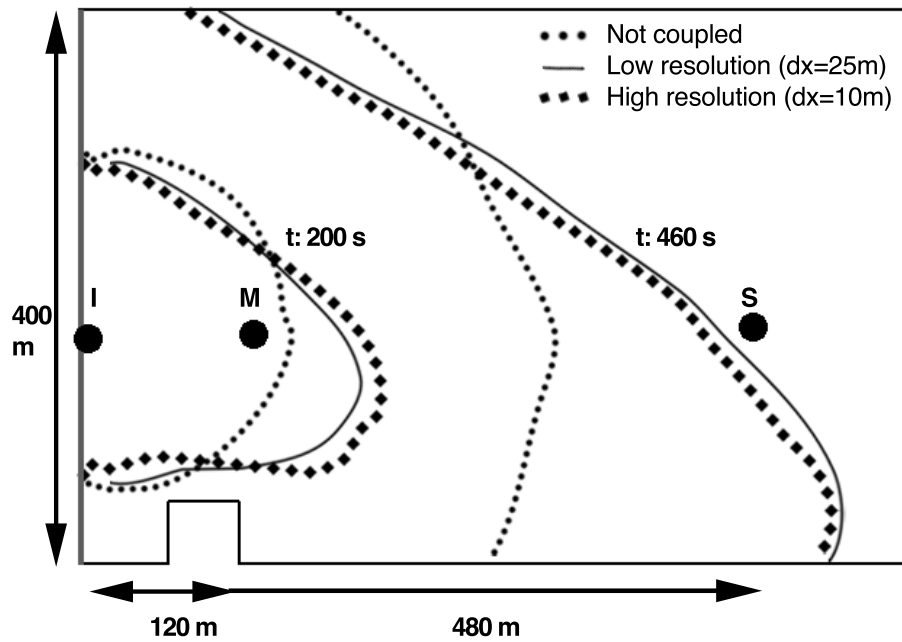
$$\Phi_w(\mathbf{x}, t) = \frac{\Phi_w^t}{\tau} \Pi_{[0,1]}\left(\frac{t - t^a(\mathbf{x})}{\tau}\right), \quad (5.22b)$$

with  $\Pi_{[0,1]}$  the gate function on time interval  $[0, 1]$ ,  $\Phi_h^t$  the total heat to be released and  $\Phi_w^t$  the total water mass to be vaporized.

### 5.2.3 Validation on the FireFlux experiment

#### Experimental setup

The experimental burn of FireFlux (Clements, Perna, et al. 2007; Clements, Zhong, et al. 2008) took place on 23 February 2006 at the Houston Coastal Center on an experimental prairie of  $0.63 \text{ km}^2$ . The experiment was designed to document the flow and turbulence



**Figure 5.17:** Bird's eye view of the FireFlux experimental setup. *I* stands for Ignition, *M* for Main tower and *S* for Short tower. Lines are isochrones at the time at which the experimental fire hit the towers.

characteristics of both the fire-atmosphere interface and the plume by means of two instrumented towers (a main one 42m high and short one 10m high). The primary goal of the burn was to achieve conditions that mimic that of a wildfire -dry fuel conditions with the fire spread being driven in the direction of the wind. On the day before the burn, total fuel loading  $\sigma$  was estimated to  $1.08 \text{ kg} \cdot \text{m}^{-2}$ . The density of the fuel is  $400 \text{ kg} \cdot \text{m}^{-3}$  with a volume-to-surface ratio of  $5000 \text{ m}$  and an average height of  $1.5 \text{ m}$ . Figure 5.17 presents the experimental set-up as well as simulated fire front lines.

### Numerical setup

Because the experiment was designed to capture both atmospheric and fire propagation properties, the FireFlux experiment has become a reference for the validation of coupled atmospheric/fire codes. It is now part of the validation test cases of WRF/SFIRE (Mandel, Beezley, and Kochanski 2011) and an important source of improvement and/or calibration of the simulations (Kochanski, Jenkins, Krueger, et al. 2011).

The fuel is assumed to be homogeneous over the burning area and the parametrization used in the velocity model (from Anderson (Anderson 1969)) resulted in a flaming duration  $\tau = 17 \text{ s}$ . Ignition temperature is taken as  $T_i = 505 \text{ K}$ , water evaporation enthalpy is taken as  $\Delta h_w = 2.3 \cdot 10^6 \text{ J} \cdot \text{kg}^{-1}$  and combustion enthalpy as  $\Delta h = 1.543 \cdot 10^7 \text{ J} \cdot \text{kg}^{-1}$ . Heat and vapor fluxes (resp.  $\Phi_h$  and  $\Phi_v$ ) used throughout the domain are considered to constantly release heat and water vapor during the burning process over the flaming area. The total amount released during this process is induced from several assumptions. The fraction of

radiant energy and combustion efficiency (portion of flaming energy) are assumed to take values  $\chi_0 = 0.30$  and  $E_c = 0.5$ , resulting in a total heat release forced at ground level of  $\Phi_h^t = 5355kJ.m^{-2}$  (with  $\tau = 17s$  this gives a nominal heat fluxes of  $315KW.m^{-2}$ ). At  $10m$  resolution, typical burning area of the fire front are about 70% of an atmospheric cell resulting in actual typical heat fluxes of  $200KW.m^{-2}$  forced in the ground level of the atmospheric model. Dead fuel moisture were approximately 9% at the time of the burn (temperature of  $17.7^\circ C$  and relative humidity of 63%), the total water mass to be vaporized is  $\Phi_w^t = 1.6524Kg.m^{-2}$ .

The simulation domain was designed to incorporate the dimensions of FireFlux experiment using a  $1000m$  large,  $2000m$  long,  $300m$  high box with open boundary conditions. Two simulations with different atmospheric resolution are considered in order to assess the relevance of the coupling, one with an horizontal mesh of  $40 \times 80$  (atmospheric resolution  $\Delta x = \Delta y = 25m$ ) and a more resolved  $100 \times 200$  ( $\Delta x = \Delta y = 10m$ ). The atmospheric vertical resolution, and more precisely the elevation of the first cell  $\Delta z^g$ , impacts the dynamics of the simulation heavily as the fire is mostly a sub-cell phenomena modeled at ground level (from the atmospheric point of view) and thus injected fluxes in a better resolved simulation produce larger responses from the atmospheric model. The vertical mesh is a geometric progression, with for the coarser simulation  $\Delta z^g = 5m$  with ratio 1.03 for 40 points, whereas for the better resolved simulation  $\Delta z^g = 3m$  with ratio 1.03 for 50 points. Initial condition is derived from a radiosonde atmospheric profile launched 43 minutes before the fire start. Lateral flow boundary conditions are forced with the sounding data for the duration of the run.

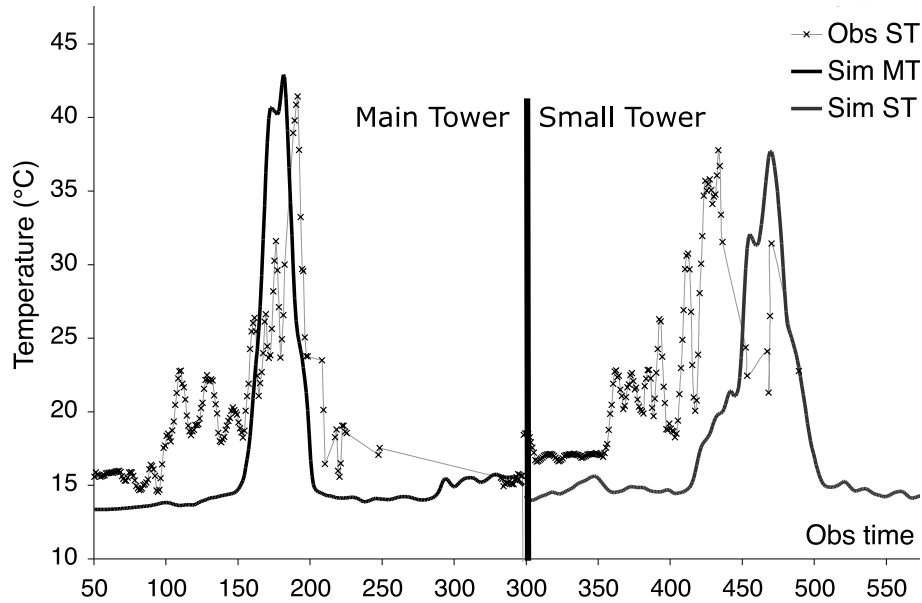
The fire propagation resolution is slightly improved in the better resolved atmospheric simulation as the spatial increment  $\delta l$  was set to  $0.02m$  compared to  $0.2m$  for the low resolution run. Filtering distance =  $0.5m$  was kept identical for the two runs and the map of arrival times is four times better resolved in the high resolution run  $\Delta x^{at} = 0.05m$  than in the lower resolution run  $0.2m$ . Due to the homogeneity of the fuel these parameters have little effect on the computed fluxes, with discrepancies of the order of 1%.

Because of the scale of the experiment, observations of the precise characterization of the fuel quantity and speed of ignition of the initial fire line were limited. Fire was ignited by two fire crews, one walking east and one westwards of the ignition front. In the simulation, the ignition procedure has been forced by imposing a custom  $0.5m.s^{-1}$  fire velocity model on a 1 meter width line ignited from the documented ignition location.

Total computational time were  $96000s$  for the high resolution run and  $4800s$  for the low resolution run. The fraction of CPU time that is used by the forest fire simulation is not directly related to the atmospheric resolution, with a smaller fraction ( $4400s$ , 5%) in the higher resolution run than in the larger resolution run ( $900s$ , 18%).

### FireFlux simulation results

Figure 5.17 shows the contours of the fire line progression for the three simulations at the observation times of  $t=200s$  and  $t=460s$  with different main direction of propagation between coupled and uncoupled simulations. Shape of the fire front line is strongly affected by the fire-induced winds with the creation of a narrower fire head that propagates faster, in better agreement with the observations from (Clements, Zhong, et al. 2008).



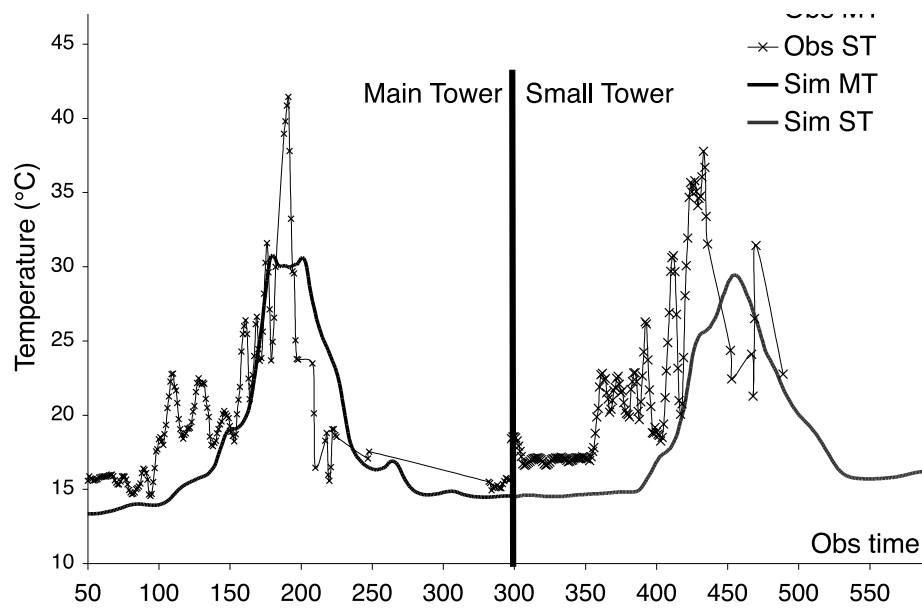
**Figure 5.18:** Time-evolution of the temperature at 10m high for the main and short towers, simulation resolution of 10m.

Quantitative comparison on the effect of the fire on the atmosphere are shown in the next figures in the spirit of the FireFlux experiment. These figures show comparisons of temperature or vertical velocity between experiment and simulation. The simulation output is taken from the corresponding height of the experimental sensors. Readers will inevitably note a discrepancy in the timing between simulated and experimental phenomena. These time lags stem from the difference of arrival times at the towers (see fig. 5.17) but as the main focus is on the dynamics of the coupling, and not in the arrival time as discussed above, the authors chose to keep these lags in the following figures.

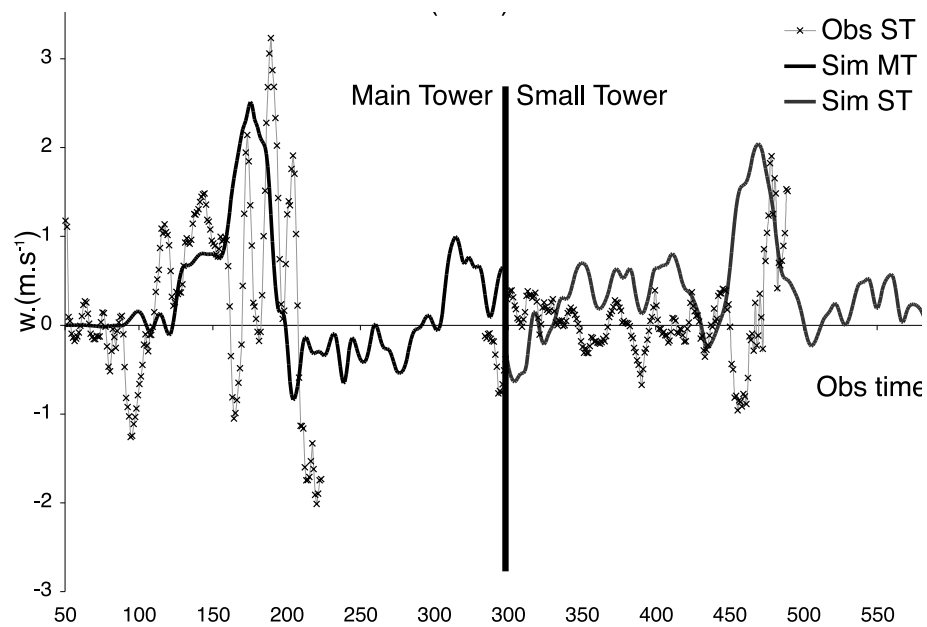
Figure 5.18 presents the results at 10m level measurements (both main and small towers) for temperature. Apart from the above mentioned time lag, the global behaviour of the coupling exhibit very interesting features. Indeed, both intensity and dynamics of the temperature increase are in close agreement with experimental values. The small difference in maximum temperature between the two towers and the temperature increase (a quick rise for the main tower and a smaller initial increase before the maximum is reached for the short tower) is observed. The heat fluxes injected during the simulations appear to be accurate enough to retrieve a temperature behavior close to observations. Compared to the lower resolution simulation (Fig. 5.19) one can note that if the general trends are similar, the amplitudes are in a lower agreement with observed values.

Figure 5.20 shows a comparison of the 10m level vertical velocity. Whereas the amplitudes of the fluctuations are smaller in the simulations than observed, the overall structure of the velocity field and resulting coupling is well simulated. A downdraft can be noted just before the fire passage followed by a fast increase when the fire front is under the location due to heating. Finally, downward motion occurs after the fire front passage in both the measurements and the simulation.

At the 28m height (Fig. 5.21), the simulated amplitude and length of the perturbation

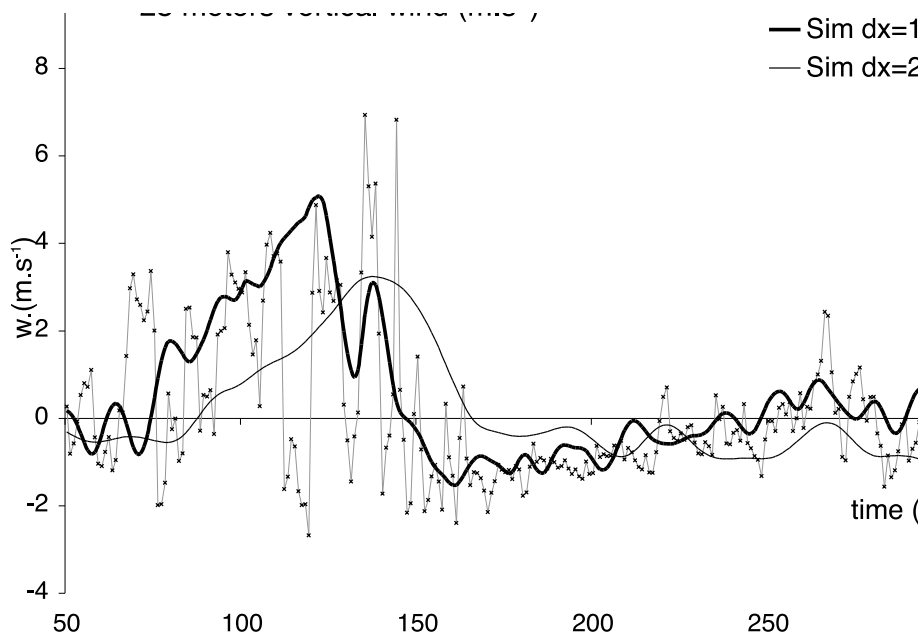


**Figure 5.19:** Time-evolution of the temperature at 10m high for the main and short towers, simulation resolution of 25m.



**Figure 5.20:** Time-evolution of the vertical velocity  $W$  at 10m for the main and short towers.





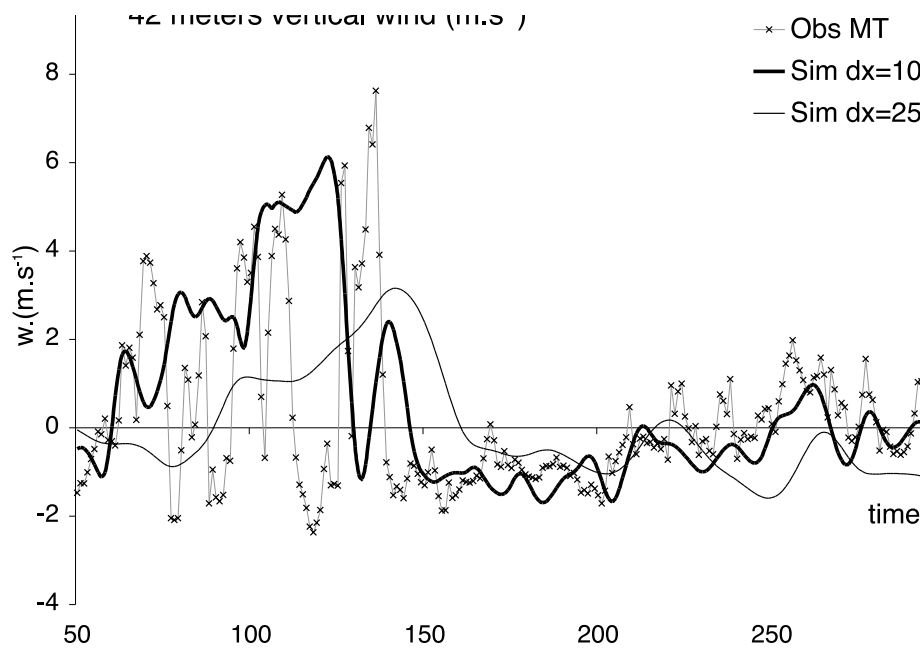
**Figure 5.21:** Time-evolution of the vertical velocity  $W$  at 28m for the main tower.

are also in agreement with observation despite the temporal shift. The lower-resolution simulation also provides acceptable results in terms of perturbation duration and behavior, with an updraft followed by a downdraft, but with smaller amplitudes.

Finally, at 42m height (Fig.5.22), the same comments could be made than for the 28m signal, showing that the plume is well transported upward in the atmosphere. Overall, for both 28m and 42m time series, wind profiles seem to correlate well with observations, especially after the fire had passed the tower with similar fluctuations that are observed as the vertical wind returns to ambient magnitude. Observed fluctuations within the plume is more subject to interpretation, numerical constraints imposed an horizontal resolution of 10 meters (larger than the flame) so that the higher frequency fluctuations cannot be well reproduced. Nevertheless, the non-resolved eddies are present as turbulent kinetic energy ( $tke$ ) as can be observed in figure 5.23. The turbulent kinetic energy observed during the experiment (Clements, Zhong, et al. 2008) was  $8m^2s^2$  at the 28m level and produced by small eddies that are shed from the fire front and therefore, are most likely too small for the model to capture accurately as suggested above. However, there is reasonable agreement between the model sub-mesh  $tke$  (fig. 5.23) and that observed during the fire front passage.

Transport of the fire perturbation can be further observed in fig. 5.23 that presents the development of a plume generated by fire heating just over the main tower. The strong buoyancy just above the fire leads to high vertical velocities up to  $10m.s^{-1}$  and entrainment on both sides of the fire by aspiration, *ie.* downdraft observed in the fire. We can also observe that  $tke$  (shading) is mainly present in areas of higher air temperature (contours), with significant perturbation of the atmospheric flow that can be found as high as 170m.

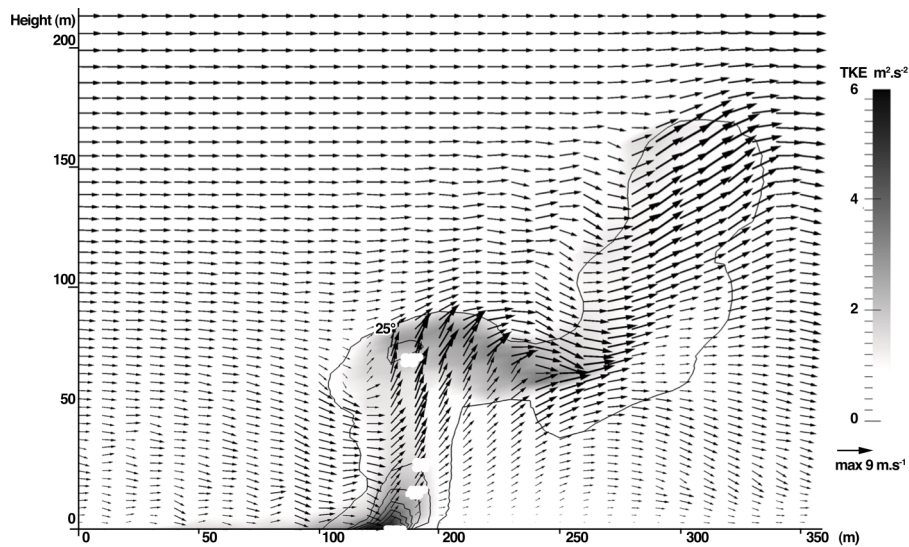
The shearing motion induced by the atmospheric flow produces instabilities and the



**Figure 5.22:** Time-evolution of the vertical velocity  $W$  at 42m for the main tower.

development of large structures that form the plume. This typical configuration of plume generation imposes a strong Courant–Friedrichs–Lewy conditions on the atmospheric simulation. The first cell level should be on the order of a few meters, and the atmospheric time-step should be lower than 0.5s to ensure that the buoyancy due to the fire is well simulated by the atmospheric model.

The coupled code MesoNH/ForeFire aims to be able to simulate large wildfires, solving complex fire-induced flow while implementing a high-resolution front advection method. The fire front velocity model can be parametrized with measurable properties of the fuel and is well adapted to coupled simulation as it uses instantaneous mid-flame wind speed just over the fire front to calculate the flame angle. The non-parallel version of the code has previously been used to perform simulations of real wildfires with results that qualitatively matches observation in terms of fire dynamics (Filippi et al. 2011a) and atmospheric chemistry (Strada et al. 2012a). This numerical simulation of the FireFlux experiment required the development of a parallel version of the code to provide results that can be quantitatively compared. It shows that the code can resolve relatively well the atmospheric coupling induced by the fire, both in terms of amplitude and the general behavior of the fire-induced winds. Fireflux was primarily designed to analyse fire-induced flows, not fire front dynamics. Fixing exact initial conditions for the fire propagation simulation was difficult because of the relative complexity of the experiment, surrounded with trees, and with limited observations of the ignition procedures and fuel characterization. After these verifications on a experimental burn, it was required to evaluate the ability of this code to scale up to large fires, about a hundred times the size of previous wildfires already simulated, and in extreme fire weather conditions (temperature over 40 degrees, very low air humidity, low to moderate winds). The case study here is the Aullene wildfire that burned more than 2000 ha in less than one day in July 2009. It aims to understand how



**Figure 5.23:** Cut in the normal direction of the wind field near the fire coloured by TKE, and temperature isocontours.

the fire modifies the dynamical structure of the surrounding atmosphere, by characterizing the turbulence in the near-fire environment.

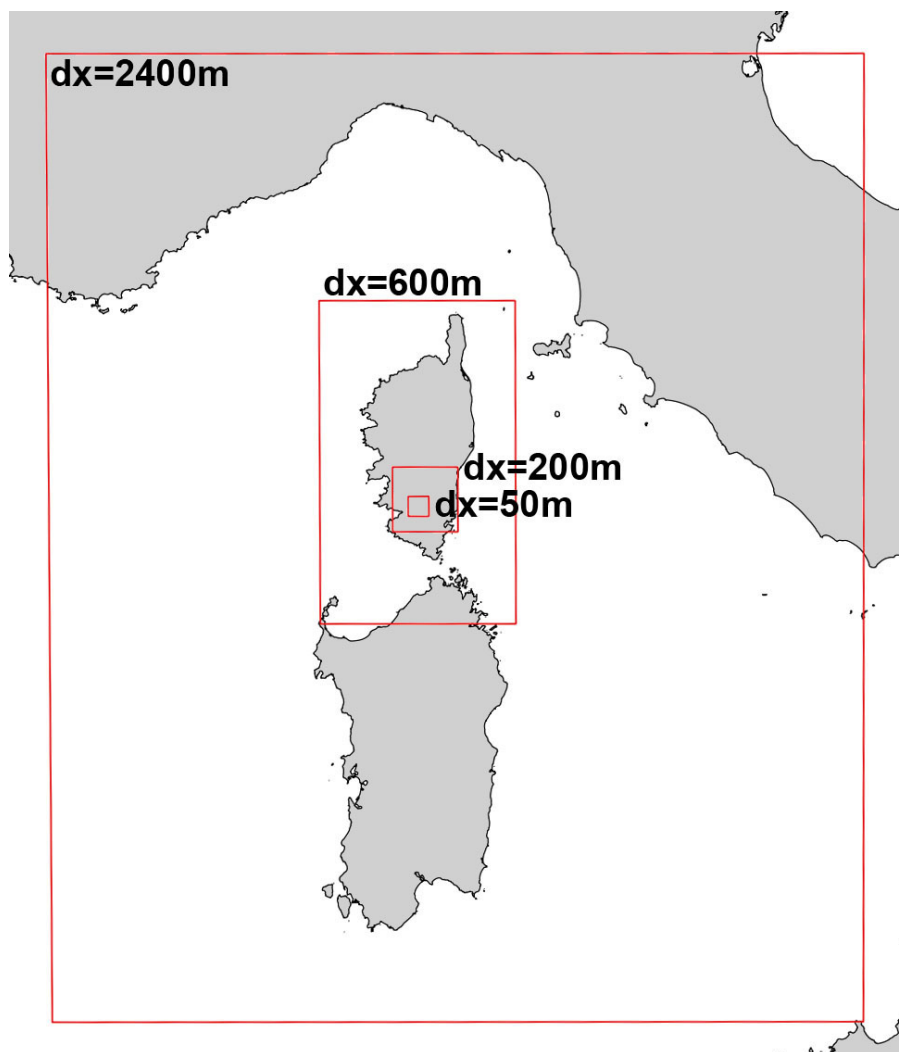
#### 5.2.4 Simulation of large wildfire

This subsection is a summary of (Filippi, Bosseur, Mari, and Lac 2018). The Aullene fire occurred on 23 July 2009, lasted five days and burned more than 3000 ha of forest with 2000 ha during the first afternoon. The same day, two other major fires (Peri, Ortolo) occurred, bringing the total burnt area over 6000 ha. The landscape of the region is typical of the Corsican mountains with a 8 km-wide and 30 km-long valley starting at sea level with elevation rising to more than 2000 m. The fire started at 13:26 UTC and was very active during the first 6 h. Fire fighting actions and an increase in relative humidity slowed down the fire progression at around 19:00 UTC, stopping the propagation at sunset (21:00 UTC). Containment actions handled during the first hour were mainly unsuccessful. Then, during the most active propagation time, all the fire fighting actions were concentrated on the north flanks to prevent the fire from expanding to the next valley.

#### Numerical Configuration

In order to resolve the development of the fire/weather system from the fire front to the large-scale atmospheric transport of the fire plume, the two-way nesting capability of the Meso-NH model is applied with four nested domains (Figure 5.24). The horizontal grid size is 2400 m for the outer domain covering  $600 \text{ km} \times 720 \text{ km}$ . The inner computational grids have grid increments of respectively 600, 200 and 50 m, covering a total area of respectively  $144 \text{ km} \times 240 \text{ km}$ ,  $48 \text{ km} \times 48 \text{ km}$  and  $15 \text{ km} \times 15 \text{ km}$  for the innermost model. The time step is 12 s for the outermost model and decreases to 6 s, 2 s and 0.5 s for the finer models. Initial and lateral boundary conditions are provided by the Aladin limited-area

model (10-km horizontal resolution) operational at Meteo-France in 2009, with updates of the coupling files every 6 h. The simulation with the coarsest resolution began on 23 July 2009 at 0000 UTC, with a progressive down scaling up to the finest resolution beginning at 1200 UTC. The vertical resolution is identical for all the nested domains, with 66 levels up to 10 km and a first level above the ground at 10-m height. All the nested models use the one and a half order closure turbulence scheme of (Cuxart, Bougeault, and Redelsperger 2000) with a prognostic TKE: the three finest resolution domains use the 3D version of the scheme, while the first one only considers the 1D version, neglecting the horizontal turbulent fluxes. In addition, the 200-m and 50-m resolution domains consider the (Deardorff 1980) mixing length, while the first two use the one of (Bougeault and Lacarrere 1989). In the same way, only the coarsest model uses the (Pergaud et al. 2009) mass flux scheme to parameterize the thermals in the atmospheric boundary layer while they are explicitly resolved at a finer scale.



**Figure 5.24:** Overview of the nested Meso-NH domains.

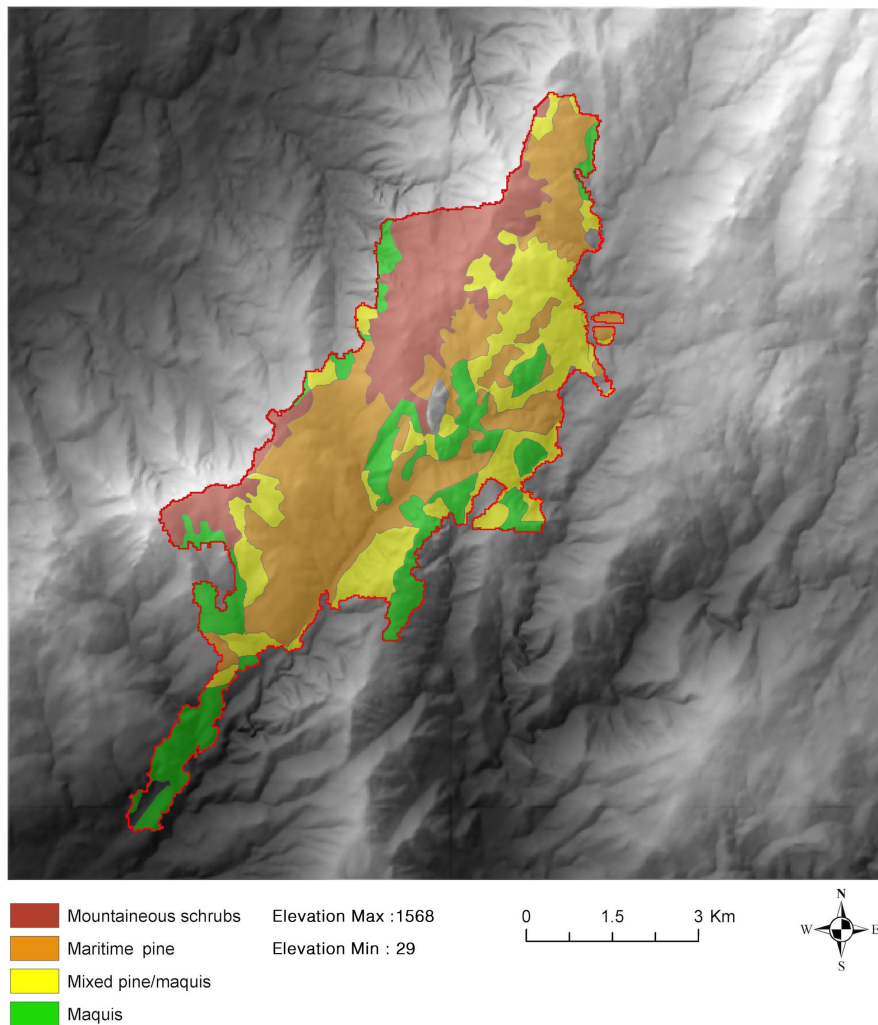
The fire propagation resolution is  $\delta l = 0.1$  m, with perimeter and AT matrix resolution

$d_e = 5$  m. The resolution  $d_e = 5$  m of the fire propagation model is limited by the actual resolution of the fuel distribution data.

Three different simulations have been run to conduct a sensitivity study of the coupling method. The main simulation is the *coupled* coupling simulation, or *feedback-on*, where the interaction between the atmospheric and fire models is two-way, as described above. An *uncoupled* simulation was run, or *feedback-off*, where the atmospheric winds are provided to the fire model, but the fire model returns nothing to the atmosphere. The third simulation is the *fire-to-atm* mode where Meso-NH wind fields are not used by ForeFire, so there is no fire-line propagation with the marker method. A pre-computed arrival time matrix is used to compute the fluxes at each atmospheric time step.

### Data Sources

The fuel layer is derived from the National Forest Inventory and is coupled with data from the IGN BD TOPO<sup>®</sup> for road and drainage networks. The Digital Elevation Model (DEM) is extracted from IGN BD ALTI<sup>®</sup> 25-m resolution. IFN classes have been grouped according to the methodology developed in Santoni et al. 2011a and use the proposed characterization of the vegetation. Figure 5.25 presents the fuel distribution over the final burnt area, with four main classes, as well as small non-burnable area providing fuel breaks. Vegetation heterogeneity, orography or small unreported older fires influence the fire propagation at small scales. These heterogeneity are not accounted for in this work, and the chosen fuel types are taken as the best guesses.



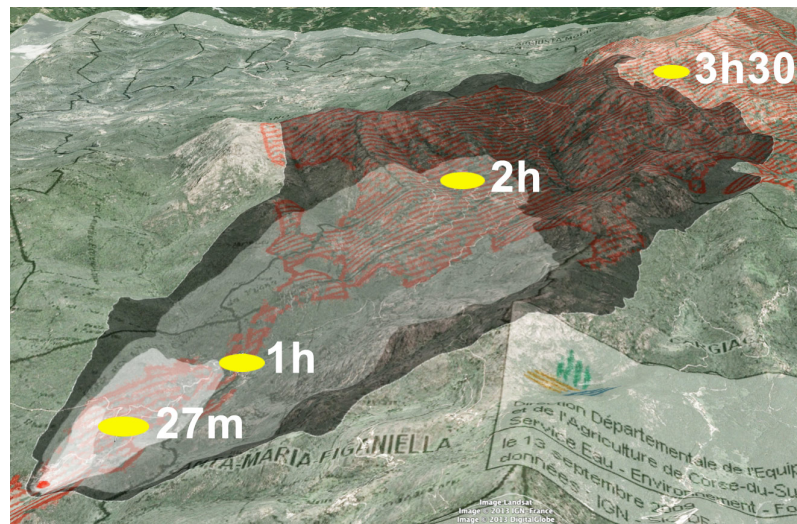
**Figure 5.25:** Overview of the fuel distributions with the four main fuel classes over the final observed fire area over elevation in gray shades.

Fuel parameters (mass loading  $\sigma$ , height  $E$  (m), moisture content (m) and heat of combustion  $\Delta h$ ) used in the front velocity model for these four major classes were set to the dead fuel load of relatively small particles (branches with diameters less than 0.01 m) that are assumed to drive the flaming fire. Pine and mixed pines' fuel estimates are equivalent fuel types that were given by foresters in charge of the area. Except from the maquis, where estimates of similar species are available from (Santoni et al. 2011a).

### Simulation Results

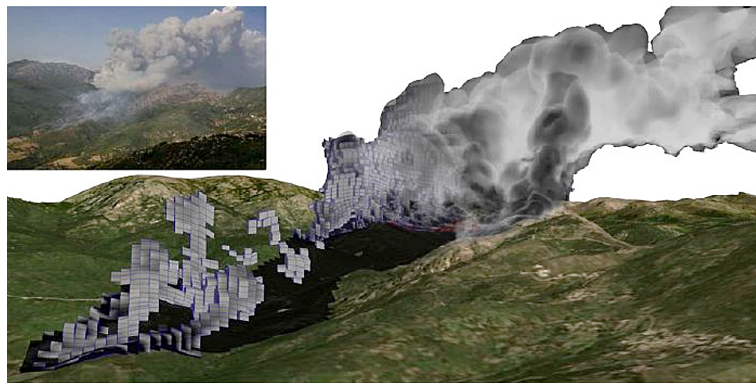
In this part, we qualitatively describe the results of the *coupled* simulation. The simulated fire behavior is difficult to assess, as firefighters were very active (except during the first hour), influencing strongly the fire propagation (and thus the local circulation), but clear reports of fire fighting actions do not exist. The only information of the fire dynamics comes from reports of fire front passage, as shown in Figure 5.26. Without taking into account

fire fighting actions, the *coupled* simulation obviously overestimates the global area burnt, except during the first hour, where the limited fighting actions were almost inefficient. However, generally, the simulated front positions appear to approximate correctly the reported location of the fire head that could not be contained.

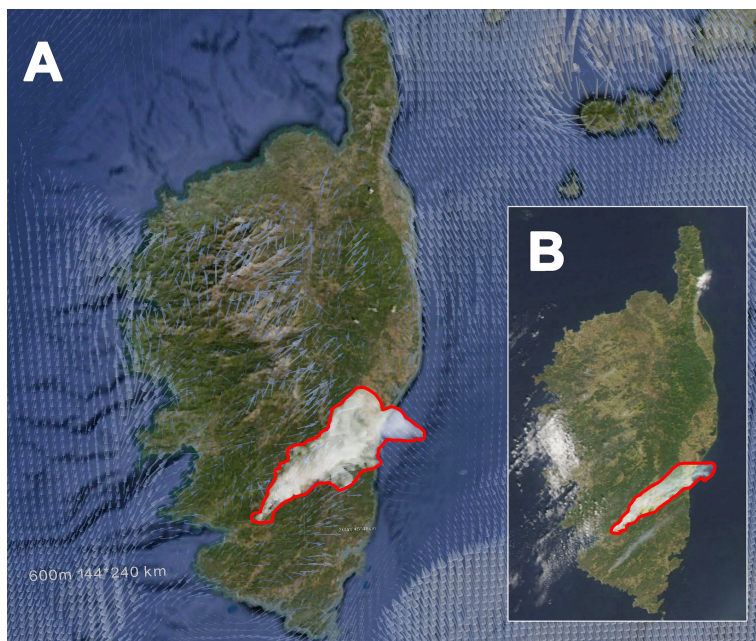


**Figure 5.26:** View of the coupled fire simulation (gray scale) 27 min, 1 h, 2 h and 3 h 30 after the beginning of the fire, with corresponding observed fire passing points (yellow marks), superimposed on the real burnt area including fire fighting actions (dashed red area). The horizontal extension at the base of the figure is 5 km.

The simulated fire plume shows a good degree of realism at the local scale at 50-m resolution (Figure 5.27a). The simulated boundary layer, analyzed in the next section, reaches approximately 2200 m above ground level in reasonable agreement with a sounding from a nearby (30 km) Ajaccio airport launched 3 h before. Once injected in the free troposphere, the fire plume is advected and diluted by larger scale winds and turbulence. The fire plume simulated in the coarser model domain at 600-m resolution is advected northeastward, 40 km downwind of the fire ignition area (Figure 5.27b). This compares well with the plume direction and extension observed from MODIS.



(a)

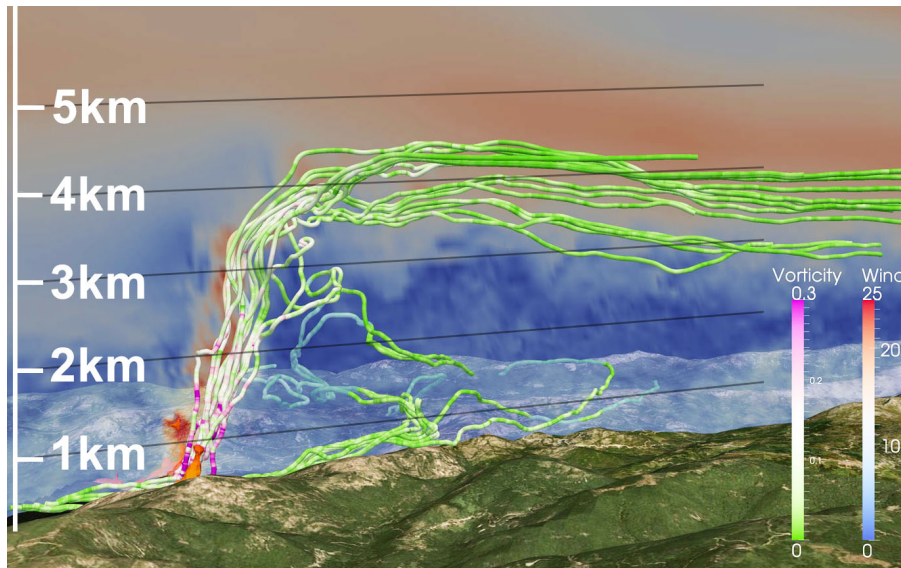


(b)

**Figure 5.27:** Simulated smoke tracer on 23 July 2009 (a) in the 50-m resolution domain compared to the plume’s photograph (at the top left) at 14:50 UTC and (b) in the 600-m resolution domain highlighted in red (A) at 15:00 UTC compared to the MODIS image (B) of Corsica at 14:50 UTC.

Figure 5.28 shows the wind acceleration near the surface and high wind speed values, which propagate along the fire-induced convective column reaching a 4500-m height. The colored streamlines reveal the vorticity magnitude in the ascending core of the fire plume. Fires are known to create vortices (Forthofer and Goodrick 2011), and although it is out of scope for this study to characterize specific whirl structures at the fire front scale, fire-induced vorticity in the vicinity of the front can be resolved because of the high horizontal resolution.





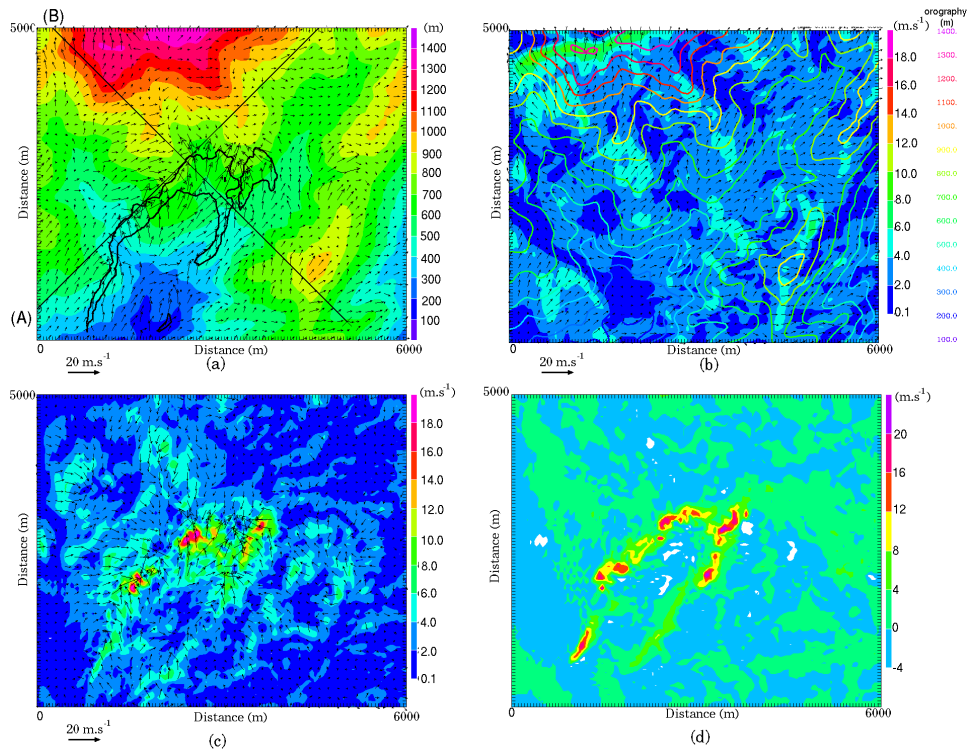
**Figure 5.28:** Vertical cross-section of the wind speed (in  $\text{m s}^{-1}$ , between blue and red) and streamlines initiated at the ground and colored according to the vorticity (in  $\text{s}^{-1}$ , between green and pink) at 1500 UTC.

We can conclude that the *coupled* simulation shows a plausible development of the fire propagation according to available observations and can be further studied.

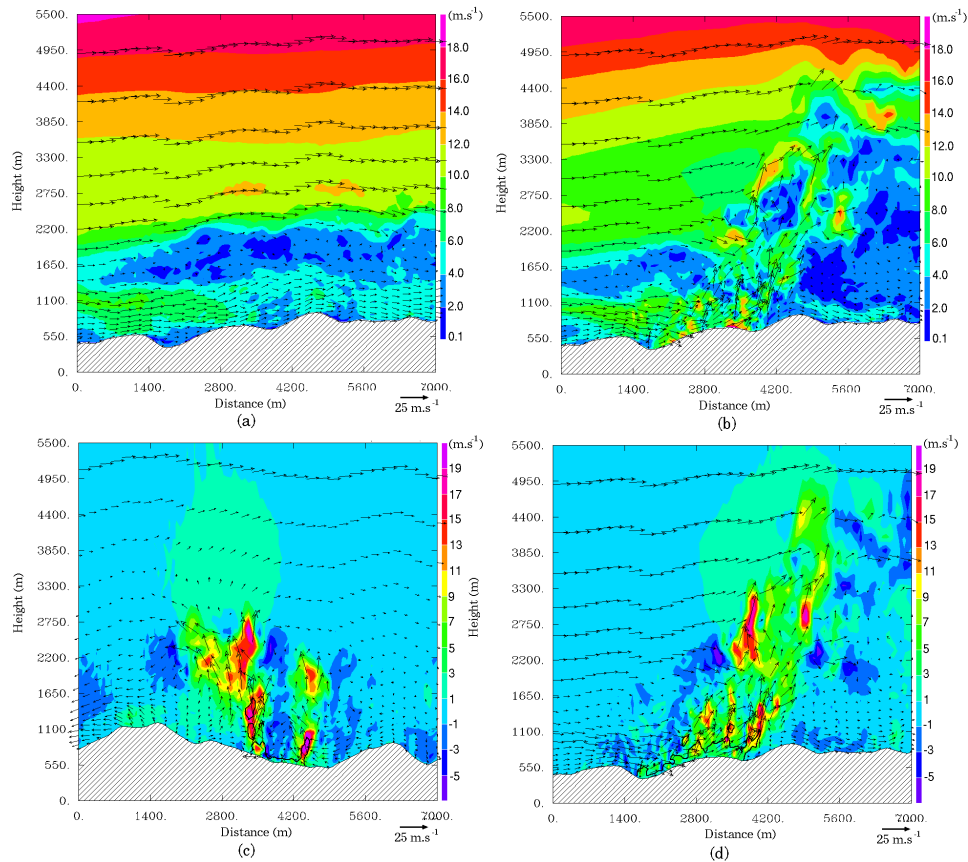
### Dynamical Plume Structure

One of the aims of the current study is to use numerical simulations to better understand fire and atmosphere interactions. Figure 5.29 presents the fire front of the “uncoupled” and *coupled* simulations at 1500 UTC with the near-surface winds. The simulated fire spreads more rapidly on the north flanks of the valley, inducing convergent winds. The difference between the *coupled* and “uncoupled” simulations is analyzed to quantify the impact of the fire on the atmosphere. Perturbed surface winds occur around 3 km around the fire front (Figure 5.29c). Fire-induced surface winds reach more than five-times the background ambient winds throughout the fire with horizontal motion differences up to  $20 \text{ m s}^{-1}$ . The fire not only modifies the dynamics near the surface, but creates a plume of almost 5000 m in depth (Figure 5.30). Instantaneous upward vertical velocities in the plume reach values of  $27 \text{ m s}^{-1}$ , with pockets of peak values being produced above the boundary layer. Comparing simulated magnitudes to the observation of other instrumented wildfires is a little bit hazardous, as we cannot expect the values to be the same for all fires. It just allows one to control the order of magnitude of the simulated values. Only few large-scale experiments (Clark, Radke, et al. 1999; Coen, Mahalingam, and Daily 2004) were conducted and mainly on crown fires. In this respect, simulated updrafts appear in agreement with Clark, Radke, et al. 1999, who observed updraft values on the order of  $20\text{--}30 \text{ m s}^{-1}$ , and Coen, Mahalingam, and Daily 2004, who reported peaks of  $32\text{--}60 \text{ m s}^{-1}$  for crown fires occurring at the highest detectable heights (about 50 m). The largest simulated downward motion occurs in the upper plume behind the fire front (maximum of  $-7 \text{ m s}^{-1}$ ), consistent with previous observations (Clements, Zhong, et al. 2008) and

simulations (Sun, Jenkins, et al. 2006).

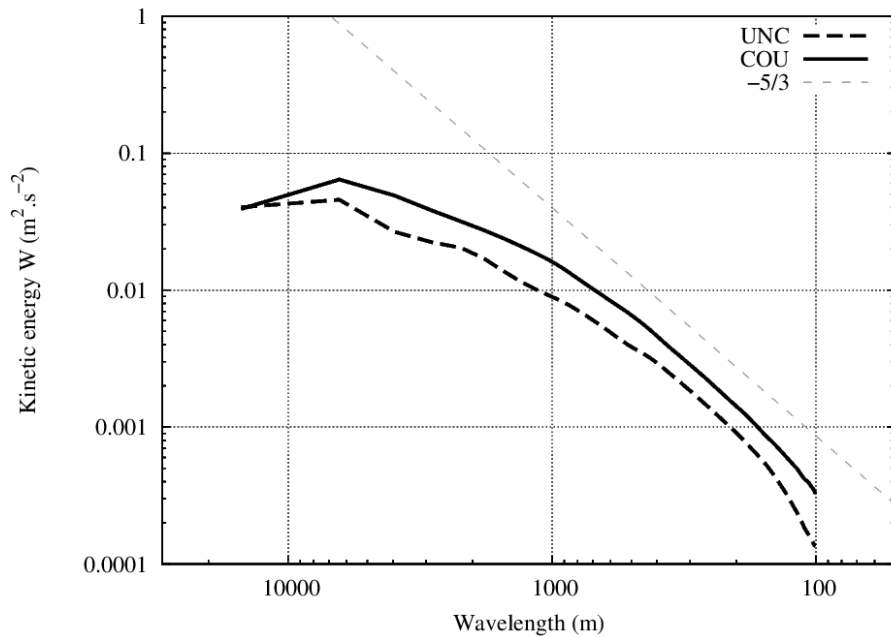


**Figure 5.29:** Horizontal cross-sections on 23 July 2009 at 1500 UTC: (a) envelop of the fire front (in black) at the ground superimposed on the 10-m wind vectors (arrows) of the coupled simulation and on the orography (color, in m) with the axis of the vertical cross-sections; (b,c) 10-m wind speed (in  $\text{m s}^{-1}$ ) with wind vectors superimposed for the (b) Uncoupled and (c) difference **coupled minus uncoupled** simulations. (d) Vertical velocity at a 300-m height (in  $\text{m s}^{-1}$ ) for the difference **coupled minus uncoupled** simulations. Orography isocontours are superimposed in (b).



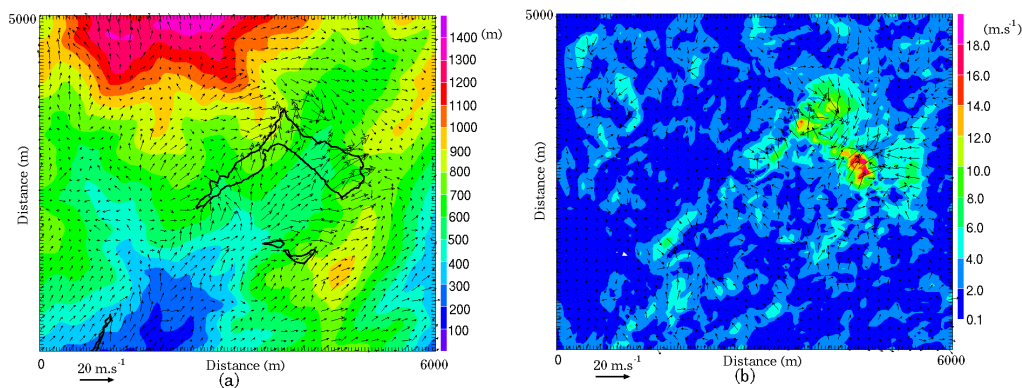
**Figure 5.30:** Vertical cross-sections on 23 July 2009 at 1500 UTC: (a,b) horizontal wind (in  $\text{m.s}^{-1}$ ) with wind vectors superimposed for (a) the Uncoupled simulation and (b) the coupled one along the direction of propagation (axis (A) in Figure 5.29a); (c,d) vertical velocity difference between coupled and Uncoupled simulations (in  $\text{m.s}^{-1}$ ) with the wind vectors (arrows) (c) across the fire front (axis (B)) and (d) along the direction of propagation (axis (A)).

In agreement with observational studies (Clements, Zhong, et al. 2008; Lareau and Clements 2017), the simulation shows increases in both horizontal and vertical velocity variances at the fire front and above, up to a 5000-m height (Figure 5.30). Simulated values are in the same order of magnitude as the LiDAR observation of (Lareau and Clements 2017) reporting maximum variance values from  $7\text{--}14 \text{ m}^2 \text{ s}^{-2}$  in a plume overshooting with comparable height. The simulated turbulence associated with the fire front is characterized by quasi-isotropic behavior with both high horizontal and vertical variances associated with fire-induced winds at the fire-front (Figure 5.29). The spectral analysis 5.31 reveals a general increase in the vertical velocity spectral energy at all wavelengths with the fire-atmosphere coupling, velocity spectra obeying the  $-5/3$  slope in the inertial subrange well.



**Figure 5.31:** Mean kinetic energy spectra for vertical wind on 23 July 2009 at 1500 UTC for the coupled (continuous line) and Uncoupled (dashed line) simulations according to the wavelength (in m). The dashed line indicates the power law with an exponent of  $-5/3$  (the Kolmogorov spectrum).

When taking into account fire fighting actions in the *fire-to-atm* simulation, the fire is less active on its lateral flanks and progresses more quickly toward the northeast (Figure 5.32), inducing an advance of about 1 km at 1500 UTC. The structure and the magnitude of dynamical fields are similar with strong fire-induced surface winds producing a convergence zone ahead of the surface and a convective column reaching the same height with strong updrafts and unresolved eddies mainly produced by shear. This underlines the systematic structure induced by the fire-atmosphere interactions in this configuration of the Aullene fire.



**Figure 5.32:** Fire-to-atm simulation on 23 July 2009 at 1500 UTC: horizontal cross-sections of (a) the fire front (in black) at the ground superimposed on the wind vectors (arrows) and on the orography (color, in m); (b) the difference between fire-to-atm and uncoupled simulations of 10-m wind intensity with wind vectors superimposed (in  $\text{m s}^{-1}$ )

### Computational Time

Computations were performed on the computer Jade at CINES (Centre Informatique National de l'Enseignement Supérieur) on 900 processors (Intel XEON types). Fire simulation overhead was estimated between 10 and 15% in the *coupled* and *fire-to-atm* cases compared to the *uncoupled* one, as can be seen in Table 5.1.

	Exec. Time (for 6000 s)	Ratio (/Real Time)	Overhead (%)
Uncoupled	7550	1.26	0.00
Fire-to-atm	8700	1.45	15.23
Coupled	8240	1.37	9.14
Coupled (depopulated)	4580	0.76	9.14

**Table 5.1:** Computation time for the different configurations.

Faster than real-time (and operational) simulations have already been performed successfully by both CAWFE (Coen and Schroeder 2013) and WRF/SFire (Kochanski, Jenkins, Mandel, et al. 2013) on larger fires, but the major asset of our simulation is mainly a higher resolution mesh (50 m compared to 200 m or more) applied to an extreme fire case. This goal was reached here by running in depopulated mode (using only two cores per compute node instead of eight), still on 900 processors (but with 3600 mobilized) on Jade, as it increases the memory bandwidth available per node. In this case, it was possible to obtain a 0.76 calculation ratio, below real time. Although this ratio is too large to consider operational uses (a forecast framework will impose a computation speed at least twice as fast), it is important to note that a factor between two and four in computation time is expected in the newer version of Meso-NH: the factor of four would correspond to the use of the Weighted Essentially Non-Oscillatory (WENO) scheme for momentum transport, but with a coarser effective resolution due to its diffusive character, while the factor of two would be brought by the WENO of fifth order (Lunet et al. 2017), or the fourth order centered scheme associated with a fourth order Runge–Kutta time-splitting marching instead of the LF scheme (Lac et al. 2018). This constitutes an interesting prospect for operational wildfire prediction. The fire-to-atm cases are here the most expensive cases mainly because this makes intensive and non-optimized use of the file system to read the fire progression file.

The coupled code Meso NH/ForeFire aims to be able to simulate large wildfires, solving complex fire-induced flow while implementing a high-resolution front advection method. The fire front velocity model can be parametrized with measurable properties of the fuel and is well adapted to coupled simulation, as it uses instantaneous wind speed just over the fire front to calculate the flame angle. The non-parallel version of the code has previously been used to perform simulations of real wildfires with results that qualitatively match observation in terms of fire dynamics (Filippi et al. 2011a) and atmospheric chemistry (Strada et al. 2012a).

The main plan is to improve fuel models, as well as the fire velocity and surface flux

models in order to better represent the combustion phase that will refine the diagnosis of turbulent fluxes at the ground level and the combustion phase of larger fuel particles. Another notable development came out of the wildfire theme, due to the flexible nature of the ForeFire solver where it is possible to implement easily different velocity and fluxes models, coupling lava and atmosphere at high resolution.

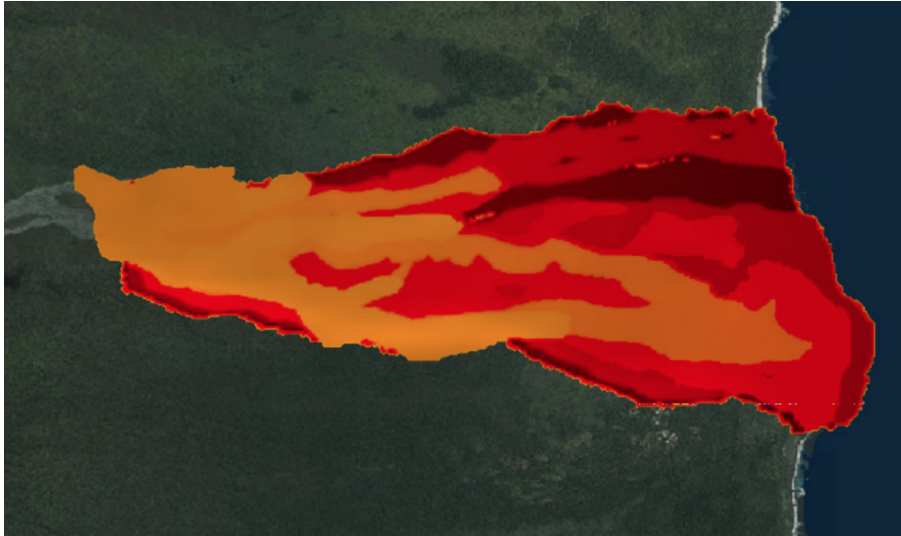
### 5.2.5 Coupled Atmosphere/lava eruption

This section presents work performed during the PhD (Durand 2016) of Jonathan Durand that was co-supervised with Pierre Tulet at the LaCy CNRS/Meteo-France laboratory at Université de La Reunion.

In April 2007, the Piton de la Fournaise volcano (Réunion island) entered into its biggest eruption recorded in the last century. More than 230 kt of SO<sub>2</sub> have been degassing and at least 180 million m<sup>3</sup> of lava have been rejected (Staudacher et al. 2009; Tulet and Villeneuve 2010). This event has been modeled by Durand et al., 2014 using a line of potential heat flux emission to represent the lava. As shown by Durand, Tulet, Leriche, Bielli, Villeneuve, Di Muro, et al. 2014, the surface SO<sub>2</sub> concentration has been successfully modeled between 2 and the 5 April, 2007 at tens of kilometers of distance from the vent. In particular on the farthest station of Cambaie (north-west of La Réunion) the agreement between the model and the surface observation was correct. Closer to the Piton de la Fournaise, in the city of Saint-Louis (south-west of La Réunion) the model largely exceeded the SO<sub>2</sub> surface concentration with a factor two of overestimation the April 4 (i.e 600  $\mu\text{g m}^3$  observed versus 1100  $\mu\text{g m}^3$  modeled) and a factor of 3 the April 5 and 6 ( 100  $\mu\text{g m}^3$  observed versus 300  $\mu\text{g m}^3$  modeled). No station was located at the vicinity of the volcano, but we thought that the SO<sub>2</sub> nearby the vent could not be correctly modeled due to the horizontal resolution of the model (500 m) and the too simplistic representation of the lava in this study. Durand, Tulet, Leriche, Bielli, Villeneuve, Di Muro, et al. 2014 Concluded that a better strategy to reproduce the volcanic plume could be a coupling system between a more detailed lava surface model and the MesoNH atmospheric model used. This is the reason why this case study was selected to illustrate and promote the impact of the coupled system ForeFire-LAVA / MesoNH to better represent the different emissions and transport of chemical species during the lava flow period.

#### Evolution of heat flux and potential temperature at the surface

5.33 Illustrates the evolution of the sensible heat flux simulated by ForeFire / LAVA on-line coupled to the MesoNH surface wind fields. From 3 April the lava flow has reached the sea. The mean temperature of the lava near the vent is lower and the resulting sensible heat fluxes decrease to 15 000 W.m<sup>-2</sup> on 4 April. Between 4 and 6 April the process continues with a weakening of the sensitive heat flows near the vent and an increase in the coastal zone impacted by the latent heat fluxes corresponding to the arrival at sea. On 6th April the area affected by the latent heat fluxes extends about 1200 m in length with a simulated maximum exceeding 700 000 Wm<sup>-2</sup> north of the front corresponding to more recent and fluid lava and two other strong zones of emissions to 500,000 Wm<sup>-2</sup>. The resulting field of potential surface temperature indicates a decrease in the temperature

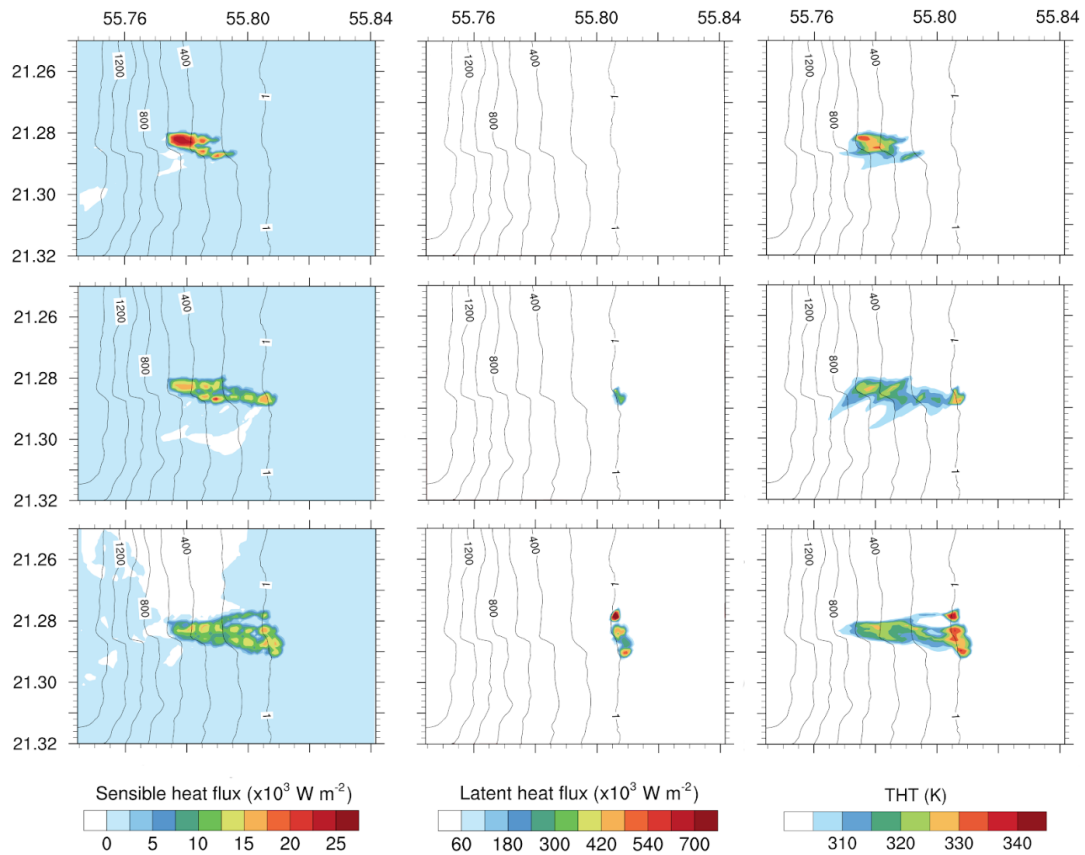


**Figure 5.33:** *Arrival Time matrix, different days represented in shades of orange to red*

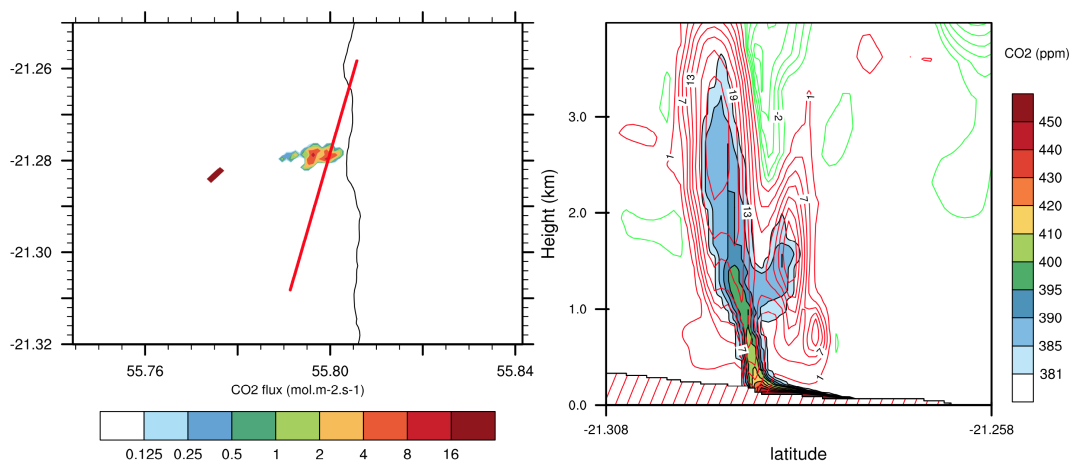
difference between the area above the lava and the environment. The consequence of the rise in potential temperature is the advent of an intense thermal breeze 5.34. An surface wind magnitude rises from 3-4 m.s<sup>-1</sup> to 10-12 m.s<sup>-1</sup> over lava flow. We can also note two convergence areas are also delimited by red lines on 5.34. The first one corresponds to a flow channel towards north east, the second is positioned towards the south border of the area occupied by lava. This local wind rise is helping the reinforcement of sensible heat fluxes by mixing and surface convection. We can estimate from (Keszthelyi, Harris, and Dehn 2003) between 5 and 10 m.s for a fluid lava of temperature 800 to 1000K a 30 % increase of sensible heat flux. This reinforced wind flow is an important positive retro-action from the lava to the atmosphere, and may start an acceleration of the local thermodynamic circulation, thus convection over the lava. One can note that this positive retroaction can only be simulated using a coupled lava/atmosphere model. When we perform a difference between wind fields on a vertical cross section over the convergence front 5.34 we can observe local convection due to thermal fluxes at the ground where the back flow is localized.

Figure 5.35 presents the CO<sub>2</sub> flux from forest burning under the lava flow on April 6 06:00 UTC. Maximum flux reaches 14 mol.m<sup>2</sup>.s<sup>-1</sup> over an area of 0.42km<sup>2</sup>. These emissions cause CO<sub>2</sub> concentrations of over 800ppm just over the burnt areas which is largely under the 5000ppm for 8h long exposition threshold. Convection over the lava transports CO<sub>2</sub> gas as high as 3000m asl 5.35. Concentrations at this altitude reaches 390 ppm which is only 10 ppm more than the background concentration, CO<sub>2</sub> is here quickly diluted with no clear signal over a few kilometers away from combustion.

The ForeFire code prove to be helpfull as a testbed for developing fluxes and velocity models for wildfire and lava propagation, but as a more general purpose code, it is possible with the same code to perform more computation of potential operational uses. Next section details efforts at performing uncertainty quantification of wildfire simulation.



**Figure 5.34:** Evolution of the sensible (left) and latent (center) heat flux in  $W.m^{-2}$  simulated by coupled MesoNH-ForeFire-LAVA on the 2nd (top), 4th (center) and 6th of April (bottom) 2007 (at 12:00 UTC). On the right, impacts on potential surface temperature as simulated. Isolines represent topography (in meters asl).



**Figure 5.35:** (a)  $CO_2$  flow models on April 6 at 06 UTC. Representation of the axis of the vertical section 4b. (b) Vertical section representing  $CO_2$  concentration (ppm) and isolines of vertical wind intensity (ascending red and subsidence green). Flux in  $mol.m^{-2}.s^{-1}$



## 5.3 Uncertainty quantification

This theme of research is developed in the frame of PhD candidate Frédéric Allaire at Inria Paris, co-supervised with Vivien Mallet (Allaire, Filippi, and Mallet 2020b; Allaire, Mallet, and Filippi 2021) and set for defense in early 2021.

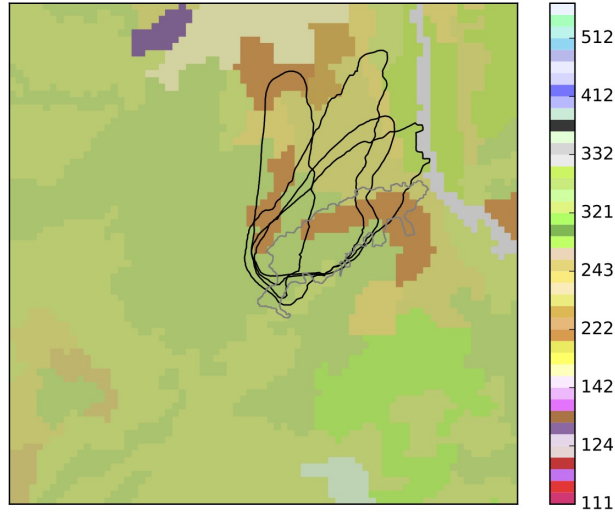
Modeling wildland fire spread is a challenging task due to the high nonlinearity of the phenomenon and the significant uncertainties in the modeling process. Instead of relying on a single deterministic prediction, an alternative consists in generating a probabilistic prediction of fire spread in order to quantify this uncertainty. In wildland fire predictions, probabilistic methods mostly focus on the uncertainty of the inputs, which is propagated through the fire spread simulators. In Cai et al. 2019, the authors investigated the uncertainty in fuel parameters via a sensitivity analysis in fire spread simulations of an actual fire; however, other influential inputs such as wind and fuel moisture content were fixed in this case study. In the context of a “crisis” situation, that is to say when a wildland fire has just started, there is significant uncertainty regarding the meteorological inputs, which are typically derived from weather forecasts. Other uncertain inputs may include fuel parameters, as well as the exact time and location of fire start. The propagation of uncertainty through the simulator is usually carried out by a Monte Carlo method where several input sets are sampled independently of a given probability distribution that describes input uncertainty. This results in an ensemble of fire spread simulations, as illustrated in Figure 5.36. The ensemble members can then be aggregated into a *burn probability map*, which estimates the probability for a zone to be reached by the fire, according to the input uncertainty that was specified for the simulations. Several works proposed a strategy to make a probabilistic prediction of fire spread stemming from an ensemble of simulations (e.g., (Finney et al. 2011; Miller et al. 2015; M.S. Pinto et al. 2016; Benali et al. 2016)), taking into account input uncertainty while other sources (notably, model errors) are usually unaccounted for.

### 5.3.1 Generation of an ensemble of simulations

Fire spread may occur in highly variable environmental conditions, as weather, vegetation state, and topography can be considerably different across the landscape and over time. Simulators that are used in an operational context often rely on an incomplete or oversimplified formulation of the underlying physical and numerical model, resulting sometimes in inaccurate predictions (Cai et al. 2019).

A major source of uncertainty in wildfire spread prediction relates to the input variables of the simulation. Wind speed, fuel moisture content, fuel parameterization, time and location of fire ignition, as well as fire duration are not known perfectly. The best estimates of these variables may result in a simulation that significantly differs from the observed spread of fire. Instead of relying on a single deterministic simulation, a promising alternative consists in adopting a probabilistic approach where several simulations are run based on different likely sets of inputs, which results in an ensemble of simulations traducing possible scenarios, as exemplified in Figure 5.36.

More formally if we introduce  $\mathcal{S}_{\mathbf{u}}(t)$  as the burned surface at time  $t$  returned by the simulator based on the set of inputs  $\mathbf{u} \in \mathbb{R}^d$ . Input uncertainty is modeled by attributing



**Figure 5.36:** An ensemble of 4 wildfire simulations. The black contours indicate some simulated fire fronts after 1h of propagation. The gray contour delineates the burned surface observed at the end of the actual wildfire. Background colors correspond to a land use raster at 80-m resolution derived from Corine Land Cover (Feranec et al. 2016) data

a probability distribution  $\mathbb{P}_{\mathbf{U}}$  to the inputs, which is now perceived as a random vector  $\mathbf{U}$ . The resulting burned surface  $\mathcal{S}_{\mathbf{U}}(t)$  is now probabilistic and traduces the probability for any location in the landscape to be burned at time  $t$ , according to the simulator and the input uncertainty. In practice, the *burn probability* at time  $t$  is estimated by the means of an ensemble of  $M$  simulated burned surfaces  $\mathcal{S}_{\mathbf{u}_1}(t), \dots, \mathcal{S}_{\mathbf{u}_M}(t)$ , where  $\mathbf{u}_1, \dots, \mathbf{u}_M$  are sampled independently of the same probability distribution  $\mathbb{P}_{\mathbf{U}}$ .

The uncertain inputs  $\mathbf{u} \in \mathbb{R}^d$  were identified in Allaire, Filippi, and Mallet 2020b and presented in table 5.2.

A major problem with these ensemble forecasts is that input parameter distribution that is defined based on expert knowledge. We extended the approach with a novel approach to generate calibrated ensembles whose input distribution is defined by a posterior PDF with a pseudo-likelihood function that involves the Wasserstein distance between simulated and observed burned surfaces of several fire cases. Due to the high dimension and the computational requirements of the pseudo-likelihood function, a Gaussian process emulator is built to obtain a sample of the calibrated input distribution with a MCMC algorithm in about one day of computation on 8 computing cores.

### 5.3.2 Calibration of an ensemble of simulations

Calibration method detailed in Allaire, Mallet, and Filippi 2021. The key elements of this calibration procedure consist in using an *a priori* distribution where the marginals have higher variance than in Allaire, Filippi, and Mallet 2020b and including the information of observed burned surfaces of the seven large fires mentioned in the present study.

The *probability density function* (PDF)  $g$  of the calibrated distribution is intended to be higher than the prior PDF  $f$  for a given  $\mathbf{u}$  when there is good overall agreement

Input	Unit	Perturbation	Distribution
Wind direction	°	Additive	$\mathcal{N}(0, 60^2)$
Wind speed norm	m.s <sup>-1</sup>	Mult	$\mathcal{LN}(0, (0.5 \log 3)^2)$
Dead fuel moisture		Mult	$\mathcal{U}(0.4, 1.6)$
Heat of combustion	mj.kg <sup>-1</sup>	Additive	$\mathcal{U}(-5, 5)$
Particle density	kg.m <sup>-3</sup>	Additive	$\mathcal{U}(-300, 300)$
Fuel height	m	Mult, individual	$\mathcal{U}(0.4, 1.6)$
Fuel load	kg.m <sup>-2</sup>	Mult, individual	$\mathcal{U}(0.4, 1.6)$
Surface-volume ratio	m <sup>-1</sup>	Mult, individual	$\mathcal{U}(0.4, 1.6)$
Direction from ignition point	°	Additive	$\mathcal{U}(-180, 180)$
Distance to ignition point	m	Additive	$\mathcal{U}(0, 1) \times \Delta_{\max}$
Time of fire start	min	Additive	$\mathcal{U}(-1, 1) \times \Delta_{\max}$
Time of fire end	min	Additive	$\mathcal{U}(-1, 1) \times \Delta_{\max}$

**Table 5.2:** Probability distribution of the perturbations on the simulation inputs.

For the first two inputs, the distribution is a truncated (log-)normal. For each of the last three inputs, we use a reduced variable in  $[0, 1]$  or  $[-1, 1]$  in the calibration procedure, and multiply it by  $\Delta_{\max}$ , which depends on the fire case, when we run the simulations.

between observed burned surface  $\mathcal{S}_{\text{obs}}$  and corresponding simulated burned surface  $\mathcal{S}_{\mathbf{u}}$ . More precisely, the PDF  $g$  can be expressed as follows:

$$g(\mathbf{u}) = \frac{e^{-\beta E(\mathbf{u})} f(\mathbf{u})}{\int e^{-\beta E(\mathbf{u})} f(\mathbf{u}) d\mathbf{u}}, \quad (5.23)$$

where  $\beta > 0$  and  $E$  is a positive “energy” function that is equal to 0 when  $\mathcal{S}_{\mathbf{u}} = \mathcal{S}_{\text{obs}}$  for each fire and increases with the dissimilarity between simulated and observed burned surfaces. Measurement of shape dissimilarity relies on the Wasserstein distance, which is a metric that appears in the field of optimal transport (see, for instance, (Santambrogio 2015) for an extensive review), and  $E(\mathbf{u})$  can be understood as an energy that is required to transform  $\mathcal{S}_{\mathbf{u}}$  into  $\mathcal{S}_{\text{obs}}$ . The definition of  $g$  is inspired from Bayes’ rule:

$$p(\mathbf{u}|\mathcal{S}_{\text{obs}}) = \frac{\mathcal{L}(\mathcal{S}_{\text{obs}}|\mathbf{u})f(\mathbf{u})}{\int \mathcal{L}(\mathcal{S}_{\text{obs}}|\mathbf{u})f(\mathbf{u})d\mathbf{u}}, \quad (5.24)$$

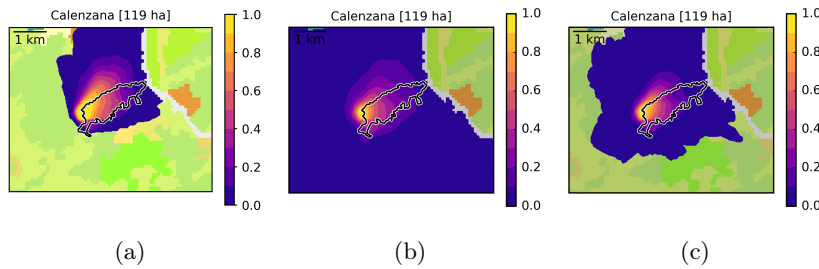
where  $p(\cdot|\mathcal{S}_{\text{obs}})$  is the posterior PDF that would be obtained from  $\mathcal{L}(\mathcal{S}_{\text{obs}}|\cdot)$ , the likelihood of the observation, and  $f$ , the prior PDF. The exponential in Equation (5.23) can therefore be seen as a pseudo-likelihood function, whose weight increases with the parameter  $\beta$ . When  $\beta = 0$ , the calibrated PDF  $g$  is equal to the prior PDF  $f$  and  $\beta = 1/2$  in the present study.

### 5.3.3 Results of calibrated ensemble of simulations

The emulation and calibration procedure proposed in Allaire, Mallet, and Filippi 2021 was applied to 7 fires that occurred in Corsica in 2017-2018 and that are presented in Allaire, Filippi, and Mallet 2020b. Results for two of these fire synthesized in table 5.3 are presented in Figures 5.37 and 5.38:

Fire name	Start time	End time
Olmeta di Tuda	2017.07.24 12:49	2017.07.24 22:00
Calenzana	2017.08.05 17:42	2017.08.05 18:42

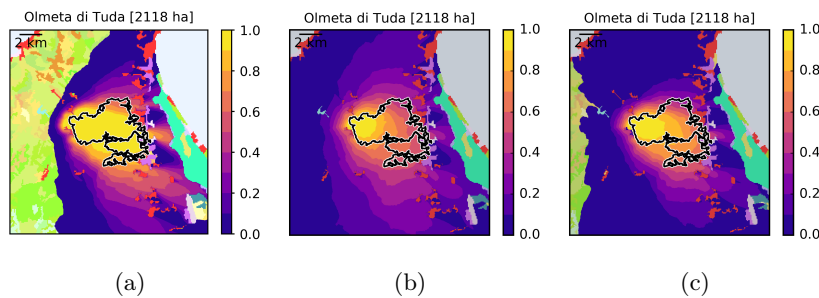
**Table 5.3:** Start time information about the fire cases. The end time is the one used in the ForeFire simulations when no perturbation is applied.



**Figure 5.37:** Burn probability maps of Calenzana fire for several ensembles. The colorbar indicates the predicted burn probability; the black and white line is the contour of the observed burned surface; background colors represent Land Cover data. a: Reference, b: Prior, c: Calibrated,  $\beta = 2$

The effect of calibration can also be investigated on individual fires. The maps of burn probability of the fires of Calenzana and Olmeta di Tuda are represented in Figures 5.37 and 5.38, respectively. We focus on the reference and prior ensembles as well as the calibrated ensemble corresponding to  $\beta = 2$ . **Non-zero probabilities reach further locations** in the prior ensembles **than they do in the reference**, which is due to the larger uncertainty on the input parameters. Calibration limits **this “extension” of the probability field** because the calibrated probability distributions mostly favor lower ROS and because the uncertainty on wind direction is much lower.

Overall, the calibration method improved the probabilistic predictions of wildland fire spread. Improving prediction accuracy is crucial especially in the field of wildland fires where human lives, infrastructures and ecosystems are endangered. Main research perspective of this work was to combine it with models for probability of ignition and values at stake to assess next day wildfire risk (developed in 6.2.1), which is relevant to fire managers, and help in the decision of firefighting actions and fire prevention planning



**Figure 5.38:** Same legend as Figure 5.37 but for the fire of Olmeta di Tuda

within a full forecasting system, FireCaster.

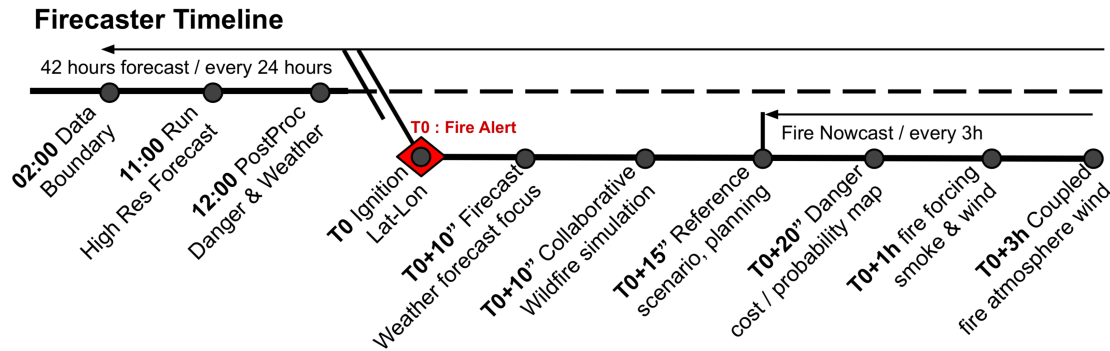
## 5.4 FireCaster wildfire forecasting system

Decision support systems for extreme weather and certain natural disasters (flood (Lepoittevin and Herlin 2015) or rain Zébiri et al. 2019) have evolved since the availability of new supercomputers allowing higher resolution and better localized forecasts. Forest fire forecasting did benefit also from those advances, with much effort being put enhancing an already very robust Fire Weather index (Van Wagner 1987) that is derived globally through the European Forest Fire Information System EFFIS (Di Giuseppe et al. 2020; San-Miguel-Ayanz et al. 2013). Nevertheless, for very local next-day fire-weather and fire behavior forecast of an ongoing fire this analysis is performed by services experts of national agencies using products built on top of weather forecast models. Creating a fire-weather specific forecasting system to serve that purpose was central to the development of the FireCaster program 2.2. The basic idea was to scale some current approaches in fire science presented in this chapter to an operational context, adapt data sources and the system so it uses a set of coherent inputs and outputs and be able to run every day.

### 5.4.1 FireCaster and urgent computing context of fire forecasting

FireCaster has been developed as a prototype suite of coherent tools and parameters and configuration to serve the purpose of supporting decision in wildfire planning using the state of the art of what super-computing can offer at the time of the project. Every choice have been dictated by the eventuality of having these codes to run in a reasonable simulation time, so that potential results may be available operationally. All codes are open-source, with the general tool-chain also publicly available. It has been designed so it covers a limited area at high resolution, and may be activated if the area is at risk. Although not a result of a basic science development, this system is central to the fire-research presented in this document because it provides a context and an experimental frame with datasets to feed and a framework to run, develop and uses simulation models. The specific basic research required was to design this context and built the simulation tool-chain that could run it.

This context is simple, because fire/weather is not always and everywhere, it is not expected to run continuously and over a large area, but to be run locally and for a limited amount of time. This focus is made when there is at threat on a specific area (that could be highlighted when larger scales system such as EFFIS(San-Miguel-Ayanz et al. 2013) provides a red alert). This alert could call to run an instance of the FireCaster system as an urgent computing service. Basically this triggers a very high resolution limited area model run around a specific location (about 200 kilometer wide) for the days of week of the red alert duration, providing high resolution fire-weather diagnostics, and boundary condition for fire behavior and propagation models in case an ignition occurs. Figure 5.39 presents the general time-line of the framework as activated, showing the fire-weather products developed as well as the fire behavior specific time-line, all bullets are detailed later in this section.



**Figure 5.39:** Firecaster timeline, with the general daily forecasts and the lower line corresponding to the potential calculations available if an actual fire is reported

All research models and approaches in the FireCaster program have been developed directly using data, and integrated within from this system and simulation context. Using real and readily available data was an added difficulty because, except for verifications purposes, we did not use a-posteriori data collection to enhance results, but instead tried to find the best possible forecast for potential events.

Research program started in 2017, with an application to the limited area of the island of Corsica. Thanks to the large data collection period between 2017 and 2020, 14 fire events of interest could be identified, as well as numerous non fire event days. In addition to provide relevant information for the verification of the current system, these 14 fires also provide a coherent dataset of initial and boundary conditions. Used with the proposed solvers it allows testing new approaches and quantify potential improvements of any single model enhancements because as a coherent system, no other part would require to be modified.

### 5.4.2 Daily forecast

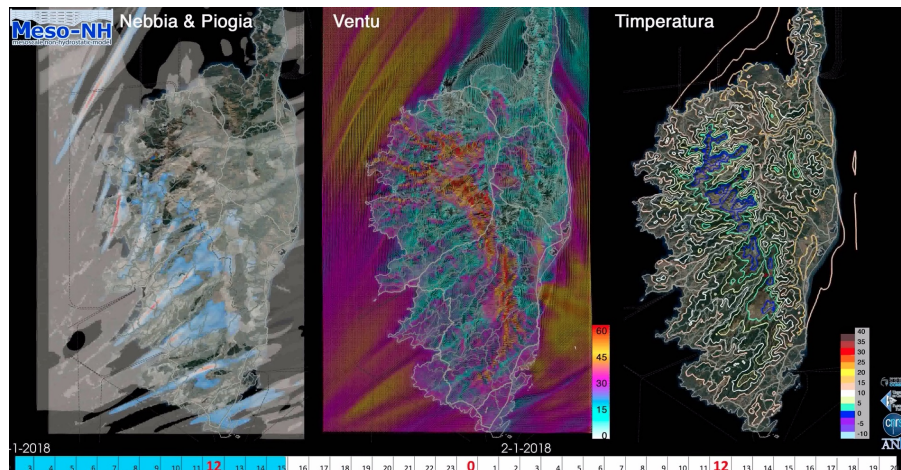
Daily forecast are performed with a high-resolution run of the limited area model MesoNH version 5.4 (Lac et al. 2018). More than the support of coupled fire/Weather simulations, Meso-NH is the atmospheric research model of the French community, maintained and developed by two laboratories associated on the research program (Centre National de la Recherche Scientifique and Laboratoire d'Aérodologie) that provided access to operational runs providing the boundary and initial conditions.

#### Boundary conditions

Boundary and initial conditions are gathered from the Météo-France archive of the AROME model (Amodei, Isabelle, and Stein 2015). The 00Z run is downloaded daily from the system and is available at around 3AM. The selected run is a 42 hours long forecast, providing boundary conditions every three hours plus the initial surface conditioning. Overall this results of 15 files to be unarchived totaling 22 Gb of data to be transferred.

### High Resolution forecast

The daily computation is performed by MesoNH on a Cartesian regular grid at 600 meter resolution and 46 atmospheric levels (up to an altitude of 7000 meters). In the application over Corsica (domain presented in Figure 5.40) this resulted in a horizontal grid of 300 by 180 points.



**Figure 5.40:** Corsica Firecast domain with (left) clouds and rain, (center) wind and (right) temperature. Provided as an animation the bottom progress bar corresponds to the displayed date and time

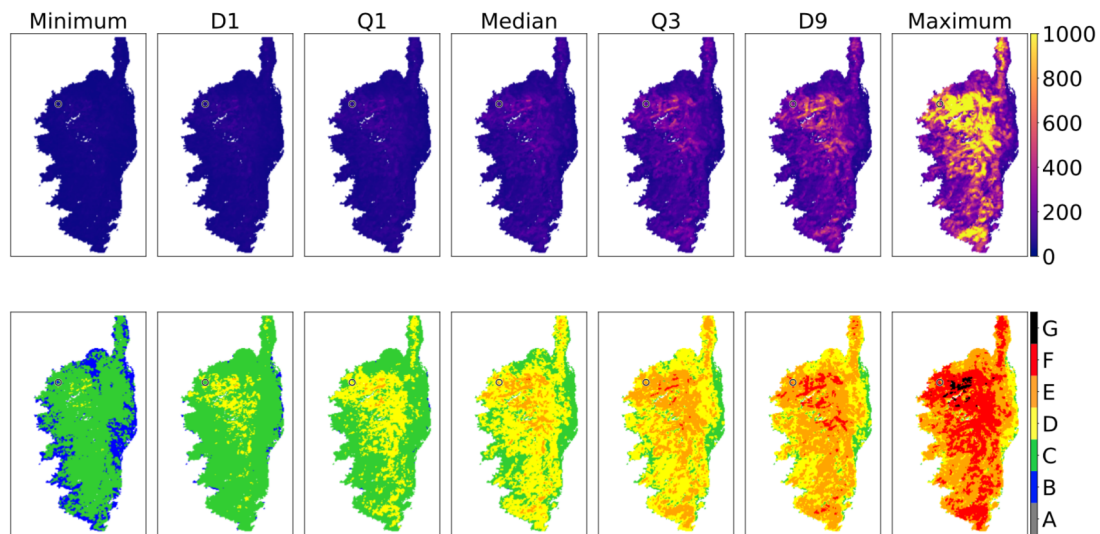
Overall computation of the 42 hours of forecast is taking an average of 2 hours on 360 CPU of the University of Corsica Brando supercomputer. In these runs, MesoNH is run coupled to ForeFire code in order to provide high frequency (2 minutes) model state outputs, resulting in 1260 output files (and 800 Gb of data containing water, temperature, cloud fraction, turbulence and U, V and W wind fields) to be post processed. Such high frequency outputs is an important point to at the same time display the complexity of local situations that can locally be very perturbed by orography and rapidly changing situations that may be critical on the field.

### Fire Danger maps

While fire danger rating systems relies solely on atmospheric variables, the fuel distribution is known to have an obvious strong effect if this fire danger were to be looked very locally. To overcome this limitation simulated maps based on the estimated surface of a simulated fire that would have start at every point of a given territory (here figure 5.41, a simulation ensemble every 80 meters on Corsica, every 10 minute). Subject of ongoing research a deep neural network is required, as a model emulator trained on a simulation dataset to reduce computational cost for more than 100 million simulations for each forecast day.

#### 5.4.3 Fire alert short-cast

The fire short-cast is triggered as soon as an alert of an ongoing ignition is reported, with the initial required information being the location and date of the ignition point.



**Figure 5.41:** *NeuralNet DeepFire 5/02/2017*

Based on 1 million simulations this probabilistic map is produce in 10 minutes. Ensemble statistics with Q1 and Q3: quartiles; D1 and D9: deciles. lower row: categorical (fire area classes).

### Local fire weather

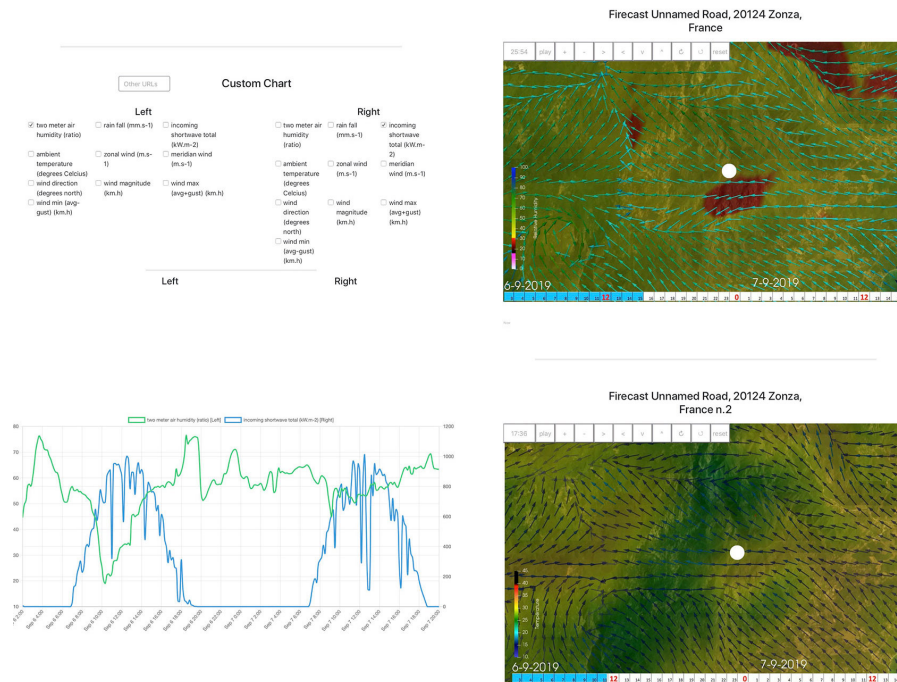
Once information on ignition point is available, the first specific use of the precomputed weather fields is to generate localized fire-weather diagnostics (on a 20 by 20 km area around the point) focusing on humidity, temperature and wind as shown in figure 5.42. These high frequency and very focused forecast helps to account for the potential local meteorological complexity at early stage of fire propagation.

Figure 5.43 presents such case at which having high resolution and frequency diagnoses is critical to the understanding of the local fire weather. Here, three small wildfire are propagating on two flanks of the same mountain, but the actual wind at the fire location is alternating between north or south because in fact it is the resultant of a convergence just above the fireline.

### Reference scenario and response planning

With the weather fields having already pre-computed, the first step to be able to simulate wildfire is to generate fuel state (in particular dead fuel moisture content) from the data of the first (ground) model level. Availability of this initial and boundary condition allows evaluating several deterministic simulations with potential modification of fuel distribution to account for firefighting actions and observation such as shown in figure 5.44. Once a reference scenario is decided, it is possible to proceed with probabilistic and coupled fire-atmosphere simulations.





**Figure 5.42:** A Quick firecast as extracted from the web system, on left interactive plots of showing here air humidity and solar radiation near Zonza, Corsica the 06 september 2019 (day of a small fire alert) it presents a sudden drop occurring at 10:00. Maps on the left corresponds to spatial distribution of humidity (top) and temperature (bottom) superposed with local wind fields. Red color threshold corresponds to very high fire danger for each parameter

### Probabilistic forecast

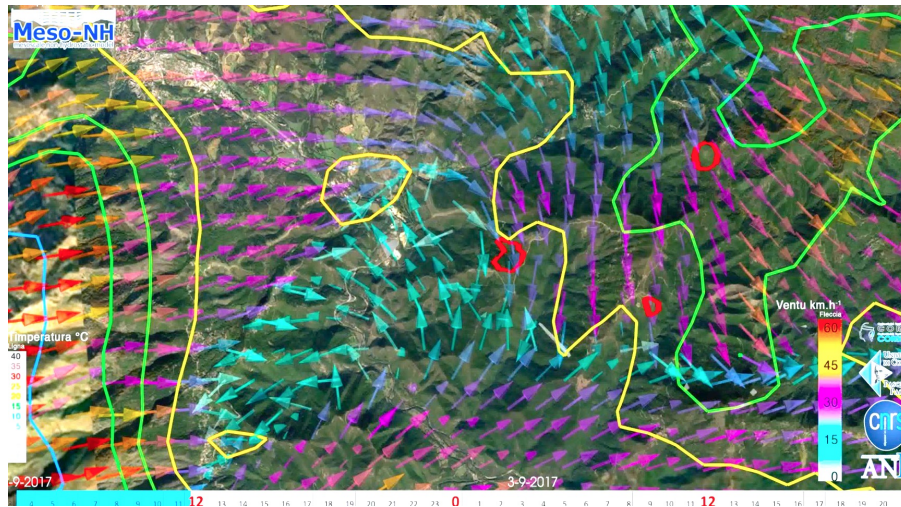
Once a reference scenario has been identified, an ensemble is run providing burn probability maps as presented in section 5.3.1.

### Smoke dispersion

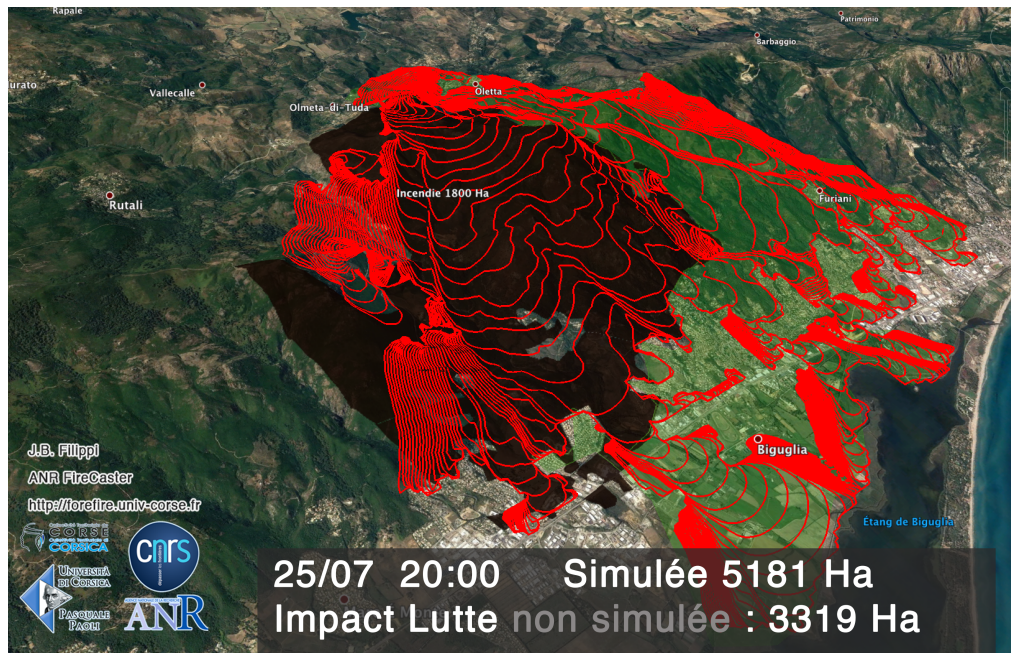
A second output, available one hour of computation is a quick estimate of smoke dispersion based on first computation is performed using advection fields already computed at 600m resolution, with high frequency (120s) outputs permitting the use of low order diffusion numerical scheme. As seen in Figure 5.45 this information has been developed hinted by that fire brigades that requested a way to quickly estimate wildfire impact on air quality and visibility.

### Coupled high resolution fire-weather forecast

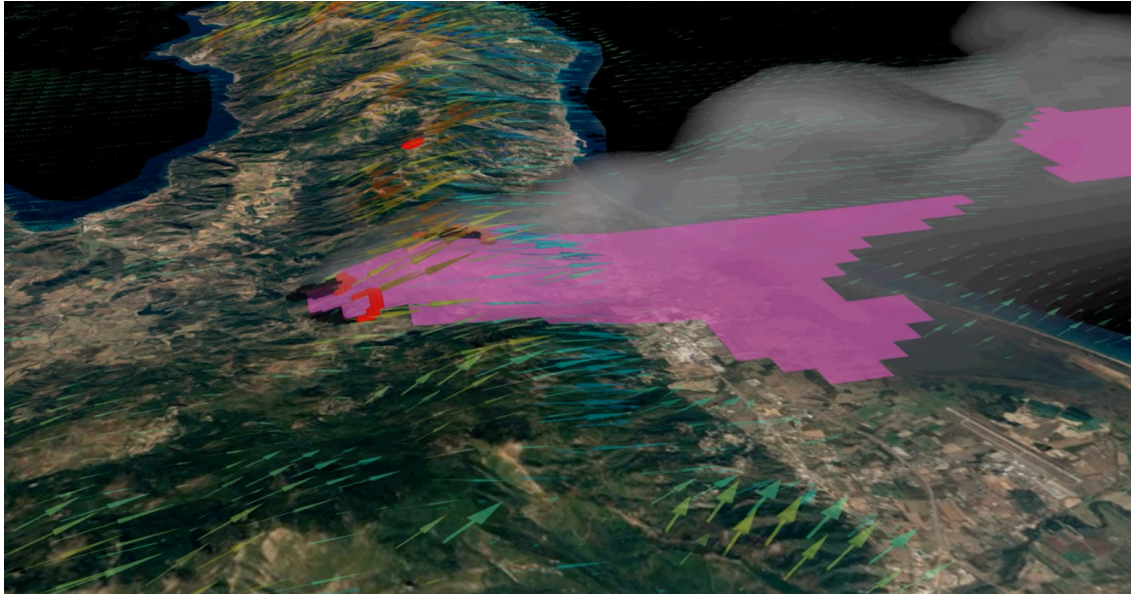
Coupled fire/weather simulation is performed following the same methodology as presented in section 5.2.4 with nested model up to 50 meters atmospheric resolution for a 6 hour-long run requiring 3 hours of computational time. Such simulation is intended to be refreshed every 3 hours and uses as fire initial condition the reference scenario defined at the stage 5.4.3. Figure 5.46 presents the output that is delivered first as an animation to provide



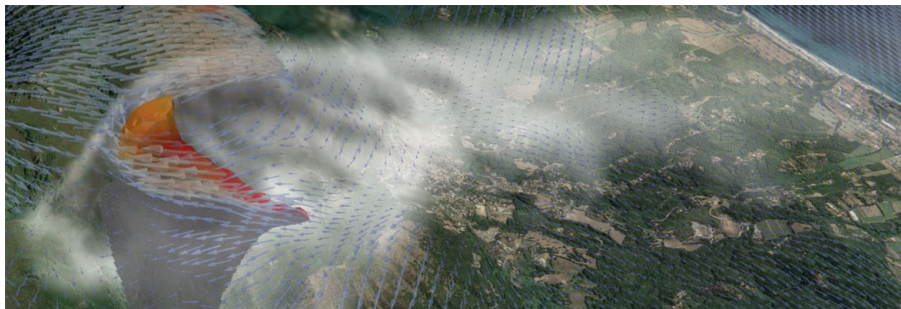
**Figure 5.43:** Fire-Weather around the Feo region in Corsica with the isolines as temperature and arrows as surface wind field showing a convergence near the red marks that corresponds to three fire of the same day. This simulation was available to the firefighters to understand the local complexity of the weather situation.



**Figure 5.44:** Biguglia wildfire simulation as generated from online simulation, red lines corresponds to 20 minutes isochrones



**Figure 5.45:** *Smoke dispersion during the Biguglia fire (2017), in pink smoke tracer presence at ground level*



**Figure 5.46:** *Simulation of the Cervione fire (02/01/2018) with arrows representing the strong wind affecting the fire head that is propagating pushed by upslope rotor in a complex configuration. Smoke tracer in shades of gray and red/orange 40 degrees temperature isosurface around the fireline*

a quick insight on the situation complexity. Simulation data is also stored for further analysis such as those presented in section 5.4.3 and allow an evaluation of the convection strength effect on the fire line.



Part III

Summary and Perspectives

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# Synthesis and perspectives

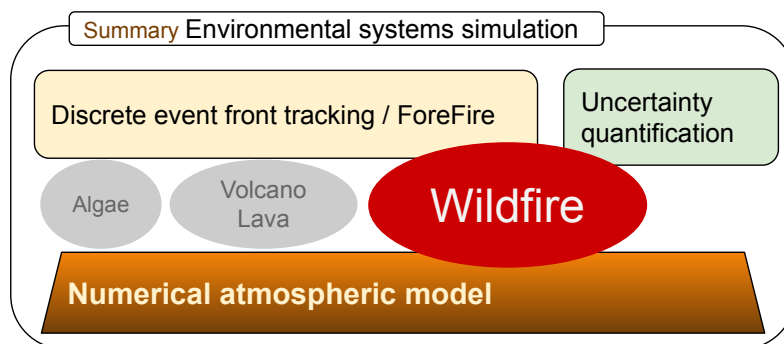
## Contents

<b>6.1</b>	<b>Synthesis of research activities</b>	<b>101</b>
<b>6.2</b>	<b>Perspectives</b>	<b>104</b>
6.2.1	Short-term perspectives and ongoing developments	104
6.2.2	Future developments	107
6.2.3	Synthesis of perspectives	109

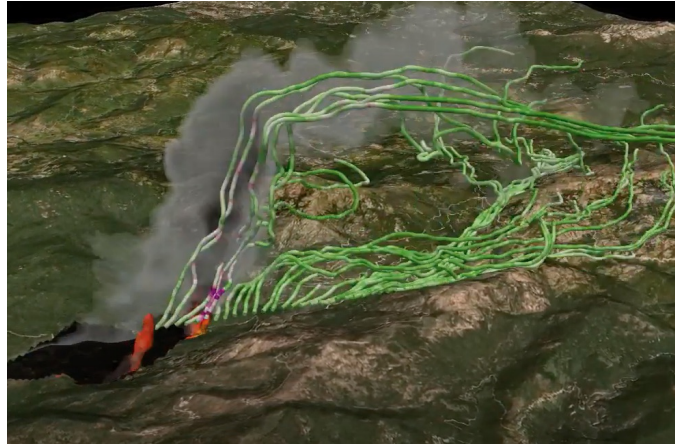
## 6.1 Synthesis of research activities

My research activities focus on the architecture and methods for the implementation and massive exploitation of environmental simulation codes: with a main application focusing on forest fire behavior and meteorology and minor applications ranging from algae dispersal to lava flow as presented in figure 6.1.

The first part of my research was to identify an adequate set of algorithms, paradigm and software architecture that will allow the specification of environmental models and their simulation (Filippi 2003b; Filippi and Bisgambiglia 2003). These were notably applied to simulation of drifting seaweeds during a post-doctorate study performed at the Ocean Research institute of the University of Tokyo (Komatsu et al. 2006; Filippi, Komatsu, and Tanaka 2010; Kokubu et al. 2019) before moving to ECMWF to learn about meteorological data and code while working on the Grib-API (Filippi, Curic, et al. 2005) geophysical data library.



**Figure 6.1:** Development of research themes, the numerical atmospheric model serves as the data source for initial and boundary conditions for all applications



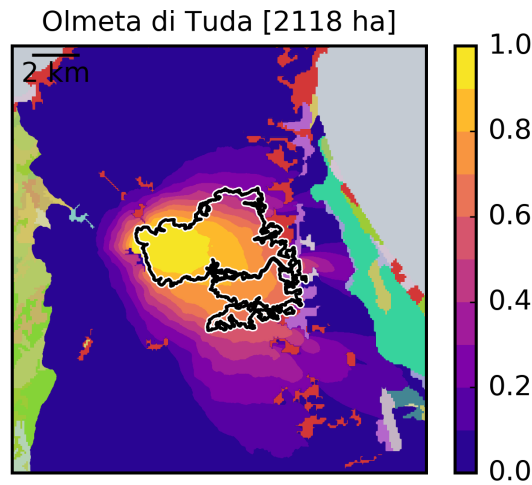
**Figure 6.2:** *Aullene fire (July 2009, Corsica)*

Smoke concentration in gray shades and vorticity along streamlines. This coupled fire/weather is able to catch the strong convection affecting winds at the fire-line. At 50 meter resolution, it requires more than 800 processor to run faster than real time.

The second part started as a new researcher at the CNRS SPE laboratory, University of Corsica with a strong focus set on wildfire. There was a requirement to develop approaches that could deliver operational results so the first step was to build from the research developed earlier a code for simulating detailed meteorological data that could both contribute to the development of science on the model of forest fire behavior and be used operationally. It led to the development of the open-source ForeFire code (Filippi, Morandini, Balbi, and Hill 2009; Balbi et al. 2009b; Santoni et al. 2011b; Kaur et al. 2016; Zhang et al. 2017) now deployed and of use by all fire department in the south-east of France. Validation of models and code was the subject of the first PhD co-advised (Bahaa Nader) (Nader Hannah Milad 2015; Filippi, Mallet, and Nader 2014b). This validation showed an evidence, the quality of initial (fuel state, slope) and boundary (wind, temperature) conditions are critical to the quality of simulation results, and the best wildfire model will only provide meaningful results on real cases it is used with quality inputs, and consequently that this data should be available when an actual fire is starting. **A major research effort was therefore provided to improve models and model inputs by coupling meteorology with fire in what is essentially open-air combustion phenomenon.**

The coupling wildfire and the atmosphere induced several challenges, with the most important was probably the different scales at which each phenomenon were observed and modeled. A very appropriate meteorological model existed in France for such challenges, MesoNH, and the coordination of a national research multi-partners program on the same subject has enabled the development of some solutions for numerically solve a forest fire propagation from combustion to the meso-atmospheric scales (Filippi, Bosseur, Mari, Lac, et al. 2009; Filippi et al. 2011b; Filippi, Pialat, and Clements 2013; Leroy-Cancellieri et al. 2014; Clements, Kochanski, et al. 2019). The coupled MesoNH/ForeFire code has been developed to the point of being able to simulate large wildfires such as the Aullene Wildfire that burned in Corsica in in 2009 (figure 6.2) (Filippi, Bosseur, Mari, and Lac





**Figure 6.3:** Burn probability maps of Biguglia fire. The colorbar indicates the predicted burn probability ; the black and white line is the contour of the observed burned surface ; background colors represent Land Cover data

2018; Lac et al. 2018). These developments also lead to coupling approach between lava and atmosphere (second co-advised PhD, Jonathan Durand) with the LaCy lab in La Reunion Island (Durand 2016).

Another challenge was the evaluation and the uncertainty error quantification in the results provided by the fire simulations in order to provide qualified estimates of the risks that evolve later in the ensemble forecasts as presented in the figure 6.3. This work on uncertainty quantification and neural-network based fire danger estimation is the subject of the third PhD (Frédéric Allaire) co-advised with Inria Paris (Allaire, Mallet, and Filippi 2021; Allaire, Filippi, and Mallet 2020a).

From this point on, most of the numerical tools and the approaches were available for the simulation of fire and fire weather, but these approaches were kept as separated prototype, and another research effort was required in order to have a fully coherent fire weather system and a context to use this system. The FireCaster program started in 2017, with the goal of proposing a prototype pre-operational platform that would provide daily high resolution of hazard and risk mapping but also of the coupled fire-weather effect of running wildfires by unifying codes, parameterization and data sources, as well as new operational diagnostics that could be derived from these new developed approaches.

## 6.2 Perspectives

This section presents my perspectives that are separated in two different time horizons, short term with yet unknown developments of ongoing activities, and longer term openings on new research fields and applications. Both are possible and because of the three main codes that are presented first.

**From ForeFire to FireCasterAPI** The ForeFire code 5.1 alone is not sufficient to perform simulation, it requires data and a way to format this data in a controlled and reproducible manner as well as standard parameterization to compare results. The FireCaster API encapsulates the solver to provides a framework for simulation incorporating also the data tiles and the code and methods to generate this data. It leverages the perspectives of the solver as it can now be applied directly on any location without a requirement to generate an initial condition file.

**Urgent computing High-Resolution short and now-casts with MesoNH** A suite of scripts and parameterization has been built as well as data coherence between the different fire behaviour models for the FireCaster tool chain. Finally, it enables with a simple input of a date and location, a limited area model to be run which will provide high frequency output data at a high resolution as well as parameterized and simulated heat and smoke injection from a surface model. Developed mainly for forest fires, this code set can be adapted to serve other purposes where similar outputs (ensemble, hazard, smoke injection) would be of interest.

**Uncertainty quantification and DeepFire** A set of algorithms and methods related to uncertainty quantification, ensemble calibration and probabilistic wildfire simulation has been implemented during the thesis of Frédéric Allaire (Allaire, Filippi, and Mallet 2020b; Allaire, Mallet, and Filippi 2021). Already applied to wildfire on some cases, the uncertainty quantification can be applied to much larger verification base. The DeepFire code is described later in 6.2.1, as a hybrid method that takes usual scalar inputs but also raster maps representing the landscape, it may be applied to any range of environmental phenomena that would benefit from local refinement in particular because of their impact that are at a lower scale that current computer simulation cannot directly solve .

### 6.2.1 Short-term perspectives and ongoing developments

These short term perspective are the subject of ongoing research programs or projects to be started that are either advanced or well-defined. Results for these perspectives are expected within the next few years.

#### Wildfire to atmosphere and extreme pyro-convection

One of the most immediate research perspectives is on the theme of fire/weather simulation, with an ongoing collaboration with the University of Evora (through a participation as an expert within an European Med Program on which they are involved). The goal is to simulate in details the complex case of the Pedrogao fire that killed 66 persons in 2017 due to a complex interaction between plumes and fire that created a such strong pyro-convective effect that fire behavior was not predictable. The large scale applications of coupled fire/weather model is also planned within the framework of three European

(H2020, Security, Green Deal) projects which have yet to be evaluated and built within large consortium of European companies and laboratories. Work on the actual coupling between fire and atmosphere is also performed within the MesoNH code with the embedded Blaze module (work on PhD candidate Aurelien Costes within the FireCaster program), but it only applied to smaller fires, which will leverage the work carried out for the coupling with the ForeFire code in order to provide a solution directly available and included in future evolutions of MesoNH code that may be used for coupled fire studies.

### **Smoke plume convection of industrial fire accidents**

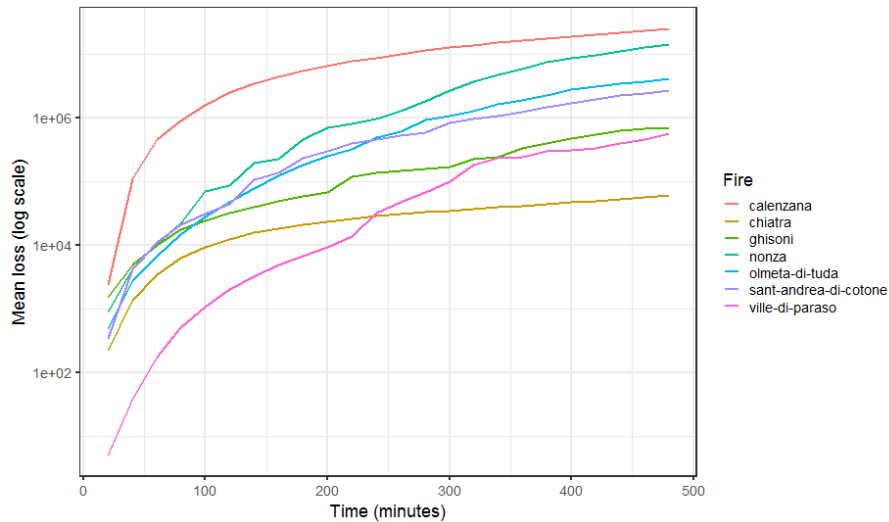
The application of an atmospheric model also generated interest within the fire safety community, especially after the incident that struck the Rouen region in France when a massive fire devastated the Lubrizol industrial site (oil and lubricants). The general approach in fire safety of industrial site is to consider complex numerical simulation models such as FDS (Mell et al. 2007) for the fire propagation and emissions in and very near fire, a large scale atmospheric chemistry model for long-range transport of these emissions and a simple analytic plume model for nearby impacts. The idea behind the development perspective is to fill this gap in near field emission, convection and transport of the smoke at the intermediate distance (100 meter to 100 km) with an approach similar to what has been done with the coupling wildfire/atmosphere. It is the subject of a project proposed to evaluation led by the CORIA lab (Rouen) with INERIS (National Industrial Risk institute) and LEMTA (Nancy) laboratories, but is likely to be developed in any cases as industrial and house fire which is a subject of growing interest within the SPE laboratory.

### **Wildfire danger and economical cost trans-disciplinary studies**

This ongoing development is the subject of a trans-disciplinary work with Antoine Belgodere, researcher in Economics in the neighboring (in Corte, Corsica) LISA (Lieux Identité eSpace et Activités) laboratory that focuses on wildfire costs in the frame of the FireCaster program.

Assessing the cost of a fire requires collecting data on land use in endangered areas. Especially, it is required to identify areas containing buildings, agricultural lands, and people in wilderness. Then to assign a value that is likely to be lost if the fire reaches a given location. Finally, it is necessary to add a risk premium to the expected cost of a given fire in order to account for risk aversion.

For all cost categories, the actual cost of a fire is highly dependent on the intensity of the fire. If a house is completely destroyed by a fire, then it seems wise to assess the cost of the fire as being equal to the cost of rebuilding the house. This represents the maximum cost that can be borne by the householder. However, damage will, hopefully, often be much lower than this maximum value (for instance, only the roof can be burned). The strategy followed to estimate the cost of a fire consists in: i- estimating the maximum cost according to the type of land use, ii- multiplying this maximum by a scale factor  $s \in ]0; 1[$  chosen to produce correct orders of magnitude. These values are aggregated in a cost map of Corsica, where each cell represents the value at risk on a  $50 \text{ m} \times 50 \text{ m}$  resolution. The first evaluations were performed on ensembles of 500 simulations of 7 wildfires that



**Figure 6.4:** Evolution of the mean cost based on 500 members for each 7 fire cases

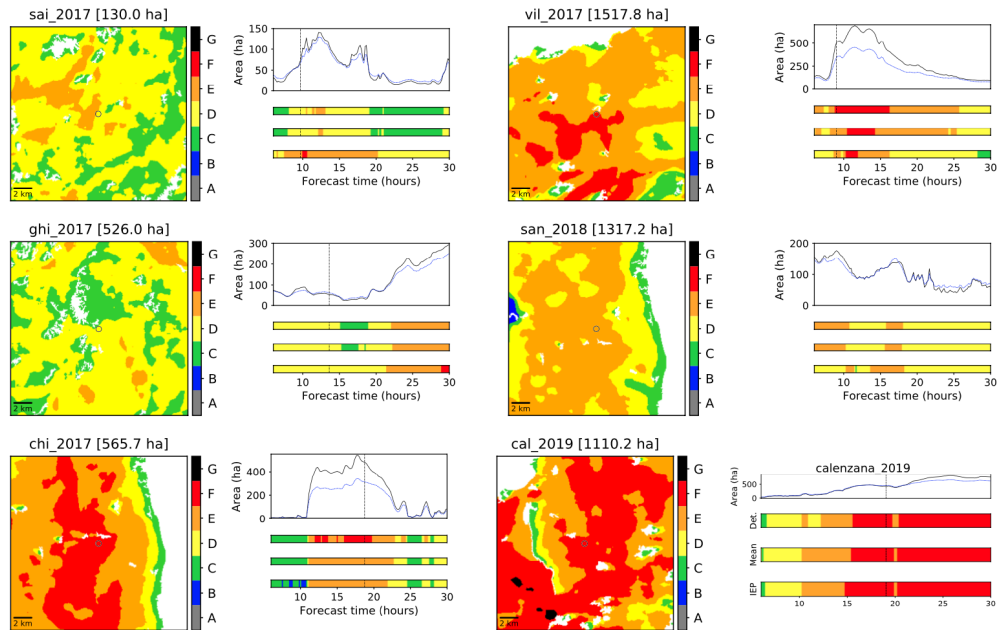
actually occurred to feed the model. For each simulation, successive polygons representing the contour of the fire are retrieved every 20 minutes. An intersection is made for each polygon of the burnt area with this map, and then a sum the values at risk of for each intersection is calculated. Finally, this risk value is multiplied by the scale factor  $s$  to obtain an estimate of the cost of the fire.

It is possible to decompose the evolution of the cost as the product of the evolution of the cost per hectare times the number of burned hectares. In 6 fires out of 7, the cost per hectare (averaged over the 500 simulations) sharply increases at the early stage (first 100 minutes). Then it evolves either slowly or becomes flat as can be seen in Figure 6.4. This 100 minutes is yet a clear finding of the study, but more importantly in terms of perspectives, this work defined a metric for cost estimation of fire simulation that is more complex than a linear relation with the area burnt and requires ongoing analysis.

### Emulation of wildfire propagation with Deep-Learning

This research theme is, like the collaborative work in economics 6.2.1, already at a very advanced state, but nevertheless provides an important perspective as to the other potential applications that it can leverage. Numerical simulation of wildland fire spread may be useful to estimate overall landscape vulnerability by an aggregation of large number of weather scenarios (Finney et al. 2011). Nevertheless, for same kind of evaluation but performed minute after minute on next day scenario, the computational time of traditional simulators is too high to be tractable over large zones such as a country or part of a country.

This issue is tackled by emulating the area of the burnt surface returned after simulation of a fire igniting anywhere in Corsica island and spreading freely during one hour, with a wide range of possible environmental input conditions. A deep neural network (named DeepFire) with a hybrid architecture is used to account for two types of inputs: spatial fields describing the surrounding landscape and the remaining scalar inputs. After



**Figure 6.5:** DeepFire based map of emulate burnt size for 6 wildfires days in Corsica. Small round matches the ignition point of the actual fire that was observed the day of the forecast with the map generated at the time of fire reported. Colors correspond to danger classes, here matching to potential fire size after one hour of free propagation with  $D > 40$   $E > 120$  and  $F > 400$  Ha. Small plots near each fire simulation correspond to the temporal evolution of potential fire area at the fire location, with deterministic in black and ensemble average in blue. The colored bar under the plot corresponds to the categorical information of the (top to bottom) deterministic, average, and compared national operational “Indice Ecllosion Propagation” index (with color not corresponding to potential area burnt but danger level)

training on a large simulation dataset, the network shows a satisfactory approximation error on a complementary test dataset. The convolutional part is pre-computed and the emulator is defined as the remaining part of the network, saving significant computational time compared to direct simulation. On a 32-core machine, the emulator has a speed-up factor of several thousand compared to the simulator and the overall relationship between its inputs and output is consistent with the expected physical behaviour of fire propagation. Figure 6.5 highlights some results that was derived from such emulators in terms of fire danger computation. With this emulator it is now possible to study ensembles of millions of simulation, performing studies on much larger areas and higher resolutions, thus opening potential developments yet to be explore in research and with operational departments.

### 6.2.2 Future developments

Research that has already been developed for wildfire ended up developing number of approaches and general themes (uncertainty quantification, deep learning, urgent computing, simulation with scenario) that eventually may be applied to other environmental threats than wildfires. With a consensus (from researchers to national policies and funding

agencies) that global warming will generate more frequent and extreme natural disasters, I envision my long term research perspective to be focused on the development of approaches to help forecast these environmental extreme events at high resolution and high frequency as well as optimized ways to mitigate their impact. A step has already been made moving from environmental systems to extreme event simulation with the FireCaster program, but the future main goal will be to leverage these developments to perform trans-disciplinary work with other phenomenon specialists (heavy rain, strong wind) and is already the subject of a prospective project within a team at SPE laboratory.

### **Towards sensor augmented extreme event forecasts with deep learning**

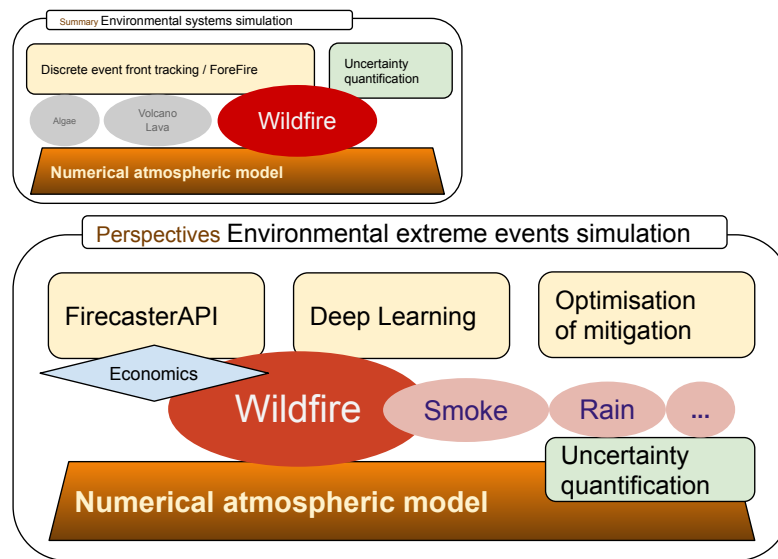
This perspective is the subject of the submitted exploratory project **SAPHiR Sensor AUgmented Prevision at High REsolution** to the ANR, coordinated in our laboratory with the collaboration of Laboratoire d'Aérodologie and Inria Paris. Its main objective is to devise a set of hybrid numerical and artificial intelligence tools and methods that provide urgent computing high-precision forecasts of localized meteorological events with the specific goals of (i) accurately forecasting intense events in order to improve warning and monitoring systems for natural hazard prevention and (ii) anticipating the production of solar plants or wind turbine farms for the management of renewable energy facilities. Our approach consists in exploiting the outputs of a high-resolution Numerical Weather Prediction (NWP) model and a variety of (real-time or post-processes) data gathered from meteorological safety sensor networks as from ad hoc local sensor networks thanks to a deep learning architecture. The system will be organized and optimized in order to increase significantly the accuracy of standard predictions over a large range of horizons (from 10 min to 48h) as respect to their space resolution and their ability to forecast the occurrence of extreme events. The project is mainly focused more specifically on two different outcomes, the prediction of events of intense storms, rainfalls and lightning strikes and wind speed/solar power prediction at some specific locations of the Corsica region.

### **Optimization of mitigation and simulation interaction**

With the ability to perform multiple wildfire simulation scenarios in a very short computational time, a potential perspective of interest would be to generate and evaluate mitigation strategies that will minimize cost, duration or impact of an ongoing wildfire. The code base to perform these simulations is FireCaster API as it is event driven, with mitigation actions (water bombers, fuel reduction,...) that may be inputted in a timetabled script, and multiplying the combinations of these scripts with a constrained scenario generator. Moreover, because of available uncertainty quantification method, as well as potential economical costs metrics (perspective 6.2.1) It already exists a path towards evaluating these scenarios and definitely a range of optimization of algorithm already explored during the calibration studies performed for ensemble fire simulations (Allaire, Mallet, and Filippi 2021). Creating new research products that can answer new questions and be active at providing mitigation actions will require developing innovative ways to view and interact with the forecasts such as augmented or virtual reality visualization of a high data volume with the premises of these tools already prototyped and presented in section 2.4.

### 6.2.3 Synthesis of perspectives

Six themes were presented in perspectives, at the same time related to the research presented in synthesis and strongly interconnected as seen in 6.6. While wildfire will continue to keep a central application position, it opens to other phenomena affecting the environment such as smoke plume dispersion, rain and potential and other extreme events that may benefit from high resolution and high frequency simulations. Overall I hope to leverage the developments in uncertainty quantification and deep learning as well as develop optimization strategies to help forecast environmental extreme events and mitigate their impacts.



**Figure 6.6:** Development of research themes, in respect to research summary (top). Numerical atmospheric model is the basis of all developments on extreme event forecasting

The general theme (and name) of my laboratory is Sciences pour l'environnement (Science for the environment). It is, since 2017, heavily equipped in super-computing facilities. Composed of more than 100 researchers, its main research teams and themes are Water resources, Natural Resource, Renewable Energies and Wildfire as well as two more oriented towards basic science (Informatics and Mathematics applied to physics). More than wildfire, the two latest themes are already clearly related to the basic research I have developed and my general long-term objective is to continue towards developing trans-disciplinary approaches with other themes that are all concerned by environmental extreme events.

The latest Saphir 6.2.2 project is already built towards this goal, and FireCaster program prove to be a successful attempt at achieving this future trans-disciplinary research in **modeling, numerical simulation and high performance computing for a better understanding of global warming heat transfer mechanisms and their local consequences.**





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## Simulation de systèmes naturels complexes, contribution à la prévision de feu de forêt

**Abstract:** Ce document présente une architecture logicielle et des méthodes numériques associées adaptée à la simulation environnementale, ses applications vont de la dispersion des algues à la coulée de lave, mais présentent un fort développement sur les incendie naturel. Le développement du code ForeFire est l'un des principaux développements réalisés comme son couplage atmosphérique, la simulation couplée feu/atmosphère, la quantification d'incertitude et l'estimation de danger incendie par apprentissage profond. Ces approches ont été développées à la frontière de deux disciplines, le génie logiciel et la simulation numérique en géophysique et combustion avec la collaboration de laboratoires nationaux et internationaux.

**Mots-Clés:** Modélisation et simulation de systèmes environnementaux. Événements extrêmes. Simulation de feux de forêts. Calcul haute performance. Simulation météorologiques incendie. Prévisions météo haute résolution. Quantification d'incertitude.

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## Simulation of natural complex systems, contribution to wildfire forecasting

**Abstract:** This document presents specific software architecture and numerical methods for environmental simulation codes, with application ranging from seaweeds dispersion to lava flow but with a strong focus on wildfire behaviors and meteorology. ForeFire code is one of the main developments carried out, as well as the realization of coupled fire/atmosphere simulation of large fires, uncertainty quantification and estimation of fire danger using deep learning. For all these studies there always have been a strong requirement to be able to deliver approaches that are or can be operational and of use with the development of a specific high resolution, computer intensive, fire weather forecasting system as a context to use such simulation. These approaches were developed at the frontiers between two research disciplines, software engineering and numerical simulation in geophysics and combustion with the collaboration of national and international laboratories.

**Keywords:** Modeling and simulation of environmental systems. Extreme events. Wildfire simulation. High Performance computing. Fire-weather simulation. High resolution weather forecast. Uncertainty quantification.

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