FIRE-RES

Innovative technologies & socio-ecological-economic solutions for fire resilient territories in Europe

D5.3

IA 5.2 brief: Modelling the EWE and smoke spread based on coupled fire-atmosphere approaches

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Abstract: We have developed a large-scale coupled fire-atmosphere simulation platform capable of producing a 24-hour forecast with an initial computation time of two hours. The system automatically updates every 12 hours, similar to meteorological forecasts, allowing for the simulation of fire advancement every 10 minutes over a 24-hour period. By integrating high-resolution atmospheric models, we address the challenges posed by extreme wildfires that generate their own local meteorology. Our work focuses on optimising computations for timely forecasts, automating the forecasting chain, and collaborating with operational services to produce actionable outputs using open-source European codes MesoNH and ForeFire.

Key words: Coupled fire-atmosphere modeling, Extreme wildfires, High-resolution simulations, Open-source codes

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Acronyms

CNRS: Centre National De La Recherche Scientifique

ECMWF: European Centre for Medium-Range Weather Forecasts

EWE: Extreme Wildfire Event

FEPC: Força Especial de Proteção Civil

HPC: High Performance Computing

HR: High-Resolution

HRW: High-resolution surface weather forecast

IA: Innovative Action

ISS: Integrative Software System

LAM: Limited Area Model

LLs: Living Labs

PM: Particulate Matter

PT: Portuguese Living Lab

TSYLVA: Tecnosylva

WP: Work Package

1. Introduction

The increasing frequency of **Extreme Wildfire Events (EWEs)** wildfires across Europe present significant challenges for wildfire management and mitigation strategies. Developing a pan-European system capable of predicting wildfire behaviour and its interaction with the atmosphere is crucial for addressing these risks. Such system should enable precise and timely simulations of fire propagation including modification to the environments such as their atmospheric feedbacks, thereby supporting decision-making processes during crisis situations.

In some circumstances, extreme wildfires can even generate their own local meteorology through pyro-convection, leading to unpredictable fire behaviour that standard meteorological forecasts fail to capture. Modelling these complex interactions is critical for improving prediction accuracy and informing effective response strategies.

1.1. Why is coupling necessary to forecast EWE, existing approaches and challenges

Several existing models attempt to address the complexity of coupled fire-atmosphere interactions. The **WRF-SFIRE** model (Mandel et al., 2011,2014) was developed in **California** to simulate fire behaviour coupled with atmospheric dynamics and has been utilised in the **Iris project in Greece** (Giannaros et al., 2019). In **Australia**, the **ACCESS-Fire** model integrates fire behaviour into the ACCESS framework for coupled simulations (Toivanen et al., 2019, Peace et al., 2022). While these models represent significant advancements, they rely on non-European codes, which may limit accessibility and adaptability for widespread European application.

For end-users, our approach distinguishes itself mainly by utilising original open-source European codes—**MesoNH** for atmospheric modelling (Lac et al., 2018) and **ForeFire** (Filippi et al., 2009) for fire propagation—ensuring sovereignty in code usage within the

European context as well as reproducibility. Both codes are freely accessible to all users, fostering collaboration and transparency within the European research community.

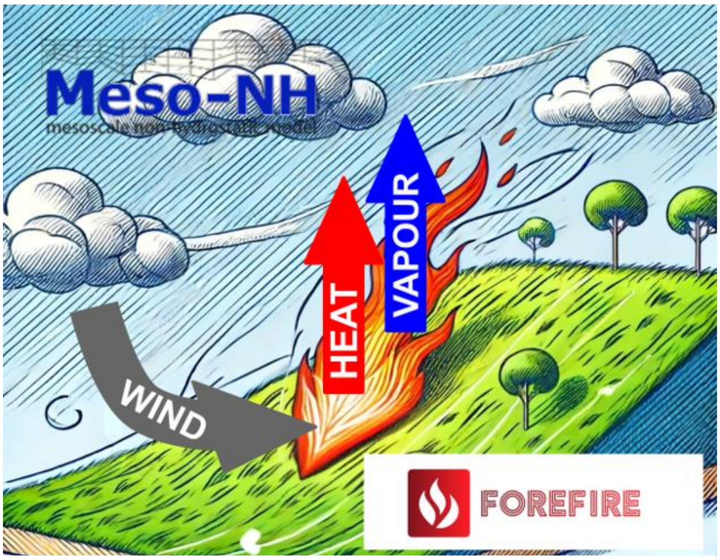


Figure 1: Main double feed-back mechanisms in the coupled MesoNH/Forefire simulation.

We remark that, besides the models mentioned above, many numerical simulations consider local atmospheric factors like surface wind and temperature, but they often do not account explicitly for the wildfire's impact on these atmospheric conditions.

The MesoNH/ForeFire approach addresses this by not only integrating local meteorological conditions, as provided by operational forecasting centres (such as ECMWF), but also by factoring in the influence of the developing fire on local weather. MesoNH simulates detailed local atmospheric conditions by solving the governing equations for atmospheric behaviour, using operational forecasts as initial and boundary conditions. Simultaneously, the heat and moisture produced by the evolving wildfire simulated by ForeFire are injected into the atmospheric grid, creating a dynamic interaction that captures the fire's effects on local meteorology (see the schematic illustration on Figure 1). Prior to the Fire-Res program, Meso-NH/ForeFire code was mainly used and developed as a scientific code, aimed to understand underlying processes on idealised or re-analysis cases. The latest developments to the code before Fire-Res (Firecaster 2022) were to develop a proof-of concept prototype (TRL 5), to demonstrate that real-time forecasting with such code would be possible. The main research and development effort within fire-res was thus to move from this prototype to a demonstrator (TRL 7).

First step was to conduct extensive scientific validation to ensure the accuracy and reliability of our coupled fire-atmosphere simulations. We tested multiple configurations and compared them with reference fires documented in the literature to define an acceptable level of precision. Notably, we performed simulations of the **Pedrógão Grande fire** in Portugal, one of the most devastating wildfires in recent European history. The associated publications by (Couto et al., 2024a, 2024b) demonstrate our model's ability to capture complex fire dynamics and interactions with the atmosphere, including pyro-convective processes (see also (Campos et al., 2023)).

In addition to forest fires, we have applied our modelling approach to large-scale urban fires to study smoke transport over vast areas. For example, the simulation of the **Lubrizol industrial disaster** in France, as detailed in (Baggio et al., 2022), highlighted the importance of accurately modelling the atmospheric transport of smoke and pollutants resulting from large fires. This work emphasised the need to consider the temperature and composition of the smoke and its interaction with atmospheric conditions to predict dispersion accurately.

Figure 2: A flammagenitus cloud

Coupled simulations are particularly crucial for fires where there is a strong coupling between the fire itself and the atmosphere. EWEs with strong convection over the fire are a typical case. Coupled simulations may also help in scenarios where wind patterns are significantly modified by terrain features because they provide a much higher temporal and spatial resolution of the wind data that is used for the front propagation. However, for the early stages of fire development (when fire is not powerful enough to modify the local weather), or for wind driven fires on relatively flat terrain, such coupling is not necessary to accurately forecast wildfire behaviour.

We remark that wildfire-atmosphere coupling is essential also for accurately modelling smoke transport, as it requires understanding how the fire plume interacts with atmospheric temperature profiles and composition. This interaction is critical because the smoke's temperature directly affects its buoyancy and vertical spread within the atmosphere. Coupled simulations capture these effects by considering the heat output from the fire and the atmospheric conditions influencing smoke dispersion, thus allowing to predict both air quality and visibility issues that can influence both firefighting efforts and public health.

1.2. Development of the Coupled Fire-Atmosphere Platform

Building upon initial capability to perform coupled fire-atmosphere simulations, the primary challenge was to produce automatic simulations within realistic time frames suitable for operational use. This required developing specific parameterizations and optimising computational processes. We tested several configurations and model resolutions to achieve this goal, with a final typical set-up presented in Table 1.

Table 1: resolution used in the automated coupled simulation system. ECMWF is a global model forcing the simulation, LAM (Limited Area Model), where coupling is computed is the sub-domain where fire is computed.

Atmosphere - Forcing	Global ECMWF forecast at 9km resolution
Atmosphere - larger model	LAM 240*240 km at 800m resolution
Atmosphere - nested fire domain	Nested 24*24 km at 160m resolution
Fire - fluxes computation / fuel map	Coupled 24*24 km at 10m resolution
Fire - fire line marker resolution	100 points per kilometre of front
Fire - fire maker advance resolution	1 metre

A typical computation case is composed of several nested models, where high-resolution domains are embedded within lower-resolution ones. This multi-scale approach allows us to capture both large scale meteorological patterns and fine resolution fire behaviour while maintaining computational efficiency. In proposed configurations, the outermost model is forced with atmospheric data from the **European Centre for Medium-Range Weather Forecasts (ECMWF)**, which provides large-scale weather forecasts. This hierarchical structure necessitated testing multiple combinations of parameters to identify those that enable us to simulate EWEs while keeping computation times reasonable.

The targeted computation time was two hours to initiate and simulate 24 hours of fire propagation, with initialization taking approximately one hour. Achieving this required careful balancing of model resolution, domain size, and computational resources. We adjusted spatial and temporal resolutions and optimised code performance to identify configurations that provide acceptable precision for EWEs within operational time constraints.

Our parameterizations focused specifically on EWEs, which are characterised by large-scale, high-intensity fires that last at least 12 hours and affect areas of at least 1,000 hectares. A pitfall is that such parameterizations are not appropriate for small wildfires, or for the early stages of a wildfire. For smaller fires, higher resolution would be needed, particularly in the distribution of vegetation and finer-scale atmospheric interactions. As an example, with an atmospheric resolution of 160 meters, a fire smaller than one hectare do not occupy even a single atmospheric grid cell, even for 100 Ha wildfire fire front is unlikely to be more than a kilometre in length, thus activating 10 atmospheric cells at the maximum with relatively little energy to actually initiate a feedback loop between the fire heat, convection, and wind pushing the fire. However, when considering high-energy/larger fires, it is possible to focus on lower-resolution models, reducing computational requirements and allowing for faster calculations. This focus aligns with the operational need to predict and manage the most impactful, particularly during their rapid expansion phases rather than the initial ignition phase.

Rapid simulation tools (results within a minute), such as ForeFire (Filippi et al., 2009) or Technosylva's FireSim (available in the ISS) are already targeted to provide insights in the first hours of wildfire, and it is only if it has been established that an event may become an EWE that coupled simulation may be requested. Early warning for potential strong convective fire has also been developed in the integrated platform in IA 5.1 and can also be a good marker to know if such coupled simulation forecasts must be triggered. It is not ensured that coupled simulation will ensure that a fire will display an erratic or extreme behaviour, but comparison between these non-coupled and the coupled simulations is a tangible indication. If the coupled simulation has a very different development compared to the non-coupled simulation performed in the ISS, it may indicate that fire is strongly influencing the local meteorology and that this influence must be taken into account.

Considering the points discussed above, the two-hour computation time required for these simulations is reasonable, as they are designed to model only wildfires with a high potential for escalation, where timely—though not instantaneous—forecasts are valuable. This approach is especially beneficial for capturing the potentially catastrophic effects of pyroconvection, which are out of reach of faster simulation tools.

Although the proposed parameterization offers a 160m resolution for the finest model, it’s worth noting that other coupled approaches used operationally in regions like Australia and California employ even coarser resolutions (around 200m) due to the generally larger fires in these areas. Our approach aims to deliver simulations that are at least as accurate as uncoupled simulations while capturing the key interactions between fire and atmosphere, where present It’s also important to note that this resolution applies to the atmospheric modelling, whereas the coupled surface spread model requires a much finer resolution (see Table 1). This higher resolution is essential for representing fine-scale obstacles (e.g., fuel breaks, roads), which have a significant impact on fire spread dynamics. In other words, the fire front’s evolution is computed at a 10m resolution, while the coupled atmospheric model operates at a 160m resolution. Heat and vapor fluxes to the atmosphere are managed through a coarse-graining procedure that allows to link coherently the two grids.

1.3. Industrialization and Automation

After optimising the computational aspects, we focused on industrialising the forecasting process to make it operationally viable. Our objective was to develop a system capable of performing simulations for any wildfire in Europe systematically and rapidly. Upon receiving an alert—such as a GPS point of fire ignition with a date or an initial fire perimeter—we can automatically retrieve all necessary data, run the calculations within the targeted two-hour timeframe for a 24-hour prediction, and produce results usable by operational personnel on the ground.

In order to achieve this the data acquisition process was automated, integrating meteorological data from ECMWF and fuel data where available. Script development and workflow implementation were essential to streamline the forecasting chain and make the pre-processsing and post-processing phases more efficient.

1.4. Collaboration with Operational Services and result delivery

This phase required strong interaction with the **Living Labs (LLs)** which are operational fire services in the **Canary Islands (Spain), FEPC (Portugal),** and **Landes de Gascogne (France)**. By re-analysing real fires that occurred in these regions—extreme fires with significant impacts selected by the LLs themselves—we worked with these services to determine what information was most useful for them in crisis situations. Our simulations produce large data files (~200 GB), which are not directly exploitable on the field. The collaboration focused on developing a limited set of representations that allow for quick and readable interpretation of results to support decision-making during emergencies. Thanks to these discussions, we identified three fire/atmosphere effects which were to be highlighted in these representations.

1. **Impact on Surface Turbulence**: How the fire induces changes in surface wind patterns and turbulence (gusts), which can affect fire spread and firefighter safety.
2. **Production and Transport of Smoke**: Smoke dispersion to assess air quality impacts and visibility issues critical for both public health and firefighting operations.
3. **Potential for Convective Cloud Formation and Self-Generated Weather**: Fire's ability to generate convective plumes that can rise high into the atmosphere, potentially creating its own weather systems leading to unpredictable fire behaviour.

In order to actually deliver the results to the field, it was also necessary to build all the procedure, codes and scripts to interface this data with the integrated platform provider of WP 5, **Tecnosylva.** To launch simulations once a fire alert is declared, the only input we require from other project partners is the ignition date and location (or, alternatively, the initial fire perimeter, if available). In the final version of the workflow, these data will be retrieved directly from the ISS integrated platform **(see D5.2 and IA 5.1)**. After these data have been downloaded, simulations are run on the CNRS HPC facilities at the University of Corsica, generating raw outputs in large files (approximately 200 GB in total). These raw outputs are then post-processed and condensed into a summary file containing only the essential information needed to create the graphical representations to be uploaded on the ISS (100 Mb). These files are then pushed towards Tecnosylva's integrated Platform that is responsible for the display and distribution of the results.

In addition to graphical outputs suitable for field use, we experimented with **augmented reality (AR) and virtual reality (VR)** technologies to enhance the usability of our data. Given the extensive data generated by the simulations, AR/VR technologies offer a different way to visualise complex information interactively. This IA resulted in several 360-degree scientific visualisations and interactive experiences where users can explore a virtual operational fire-prone environment where meteorological conditions and fire dynamics are graphically and dynamically represented, allowing multiple users to navigate the virtual environment simultaneously. While not operational (as operational or real-time VR it was not the focus in this IA), the goal of these experiments were limited to two aspects:

- **Operational Support**: Providing an experiment to investigate further visualisations that are more intuitive to display complex fire-atmosphere interactions.
- **Public Awareness**: Enhancing communication with the public to raise awareness about fire dangers and fire-atmosphere interactions, contributing to improved community preparedness.

1.5. Limitations, Data Challenges and Collaboration

A limitation we encountered was the availability and quality of fuel data at the desired resolution. While we aimed for a 10-metres resolution to capture fine-scale fire behaviour, fuel type classifications are not uniformly detailed across the entire European territory. We are collaborating with other innovative actions within the **Fire-Res** (D5.4 lead by F.Pirotti) program to enhance the granularity and accuracy of fuel type information that we hope to address before the end of the project. Another limitation is that, although the code to run the simulations will remain available after the project ends, the simulations will no longer be operational, as they require a supercomputer provider and ongoing supervision to run the service.

This introduction already provided a summary of the actions that have been developed in this innovative action. The different section in this report details the three phases of development before conclusion in a not too technical fashion (all parameterisations can be found in either the scientific publications by the same authors, or directly in the open software repository). In the first, **Optimization of Computations**, we detail how an optimised parameterisation set has been developed. In the second section, **Automation of the Forecasting Chain**, we explain how we automated the forecasting process, including data acquisition and sources, script development, and workflow implementation for running automatic coupled simulations. In the third section **Case Studies and Development of Output Tools/Files**, we present three main cases that have been analysed with LLs to develop meaningful representations and the integration into the ISS. Finally, in **Conclusions, limitations and perspectives** we summarise further the system while identifying limitation that opens to new research perspectives on the subject.

2. Optimization of Computations

In operational wildfire management, the ability to produce timely and accurate simulations is crucial for effective decision-making. However, it's important to define what we mean by 'real-time.' Typical 48-hour weather forecasts require several hours to compute, but because they run continuously and are updated every 3 to 6 hours, there is always an available forecast that has been computed in advance—something we often take for granted. In other words, our simulation’s operational workflow should be viewed more within the framework of weather forecasting, rather than being compared to instantaneous wildfire simulation tools. In wildfire prediction, the complexity arises from the unpredictable nature of ignition timing, making an initial delay for simulation setup unavoidable. Ideally, a 24-hour forecast would be available instantly. However, coupled fire-atmosphere models are even more computationally demanding than typical weather forecast models, making instantaneous forecasts unrealistic. Instead, producing the first 24 or 48 hours of forecast will always require a few hours after an alert is issued. During this initial delay, coupled forecast data is unavailable, and the optimization efforts described here focus primarily on minimizing this initial delay.

Once this first computation is performed, and just like a weather forecast, there will always be a readily available forecast. The only requirement thereafter is to perform a refresh (every 3 or 6 hours) to take into account the latest observations and boundary conditions. The constraint for refresh is that the actual computation duration should be less than the refresh update time (the 3 or 6 hours).

The first part of this section is to define a typical use case for such a situation, in order to identify an acceptable **initial forecast delay.** Then three different configurations are presented and compared before a generalisation of the parameterisation.

2.1. Focus on Extreme Wildfire Events

To make coupled simulations feasible for operational use, the focus is directed toward extreme wildfires—those likely to become large or enter a phase of rapid expansion. These fires typically cover several thousand hectares, have fire fronts several kilometres long, and occur under atmospheric conditions conducive to strong fire-atmosphere interactions.

Because coupled simulations are only intended for such fires, there must exist an initial assessment stage at which an event is classified as having the potential for extreme development. In the standard targeted operational workflow as defined in IA 5.1 and D5.2, this assessment is conducted using the integrated platform with rapid fire-only simulation and assessment of the convective potential. If indicators suggest that the fire could escalate significantly, a coupled simulation is requested. The goal is then for simulation results to be available much before the fire reaches its phase of rapid expansion.

Experience from extreme wildfire in Portugal (Benali et al., 2023), that the phase of very rapid expansion usually does not occur in the first few hours of the fire. This provides a reasonable window—estimated at two to three hours—during which simulations can be launched. Moreover, the rapid expansion phase was rarely spread for a period of more than 12 hours, so an initial forecast for 24 may be acceptable. The target for **initial forecast delay has been set to 2 hours for 24 hours forecast.**

2.2. Selection of optimal resolution and simulation context

Initially, our reference numerical configuration for the coupled MesoNH-ForeFire model (Filippi et al., 2018, Couto et, al 2023) demonstrated a computation speed of approximately half the real-time duration of the simulated event. For example, simulating 24 hours of fire propagation could take up to 12 hours of computation time. In these simulations, the goal was mainly to demonstrate that faster than real-time was possible, and a large amount of computing time was devoted to generating frequent outputs. Nevertheless, the challenge is still to find a sixfold increase in efficiency, going from 12 to 2 hours of computation. Several other constraints and requirements were also identified:

- **Parallelisation limit:** A standard strategy to increase the speed is to add more processors. Nevertheless, it has a strong limit, the MesoNH code we are using decomposes the whole domain on the horizontal plane to assign a subset of points to each processor, so theoretically a horizontal grid of 100 by 100 can be decomposed into a maximum 10.000 subsets of 1 point. But this decomposition is very suboptimal as the supercomputer will spend much more time exchanging data than solving the physics. Because of that, the effective limit is around 100 points per processor, with an optimal efficiency around 250 points. So, an unlimited number of processors is more related to an unlimited number of points. But the hard limit in our case is that each single processor must be able to provide a 24-hour forecast on its local 100 points or more subset.
- **Courant condition:** Atmospheric simulation advances with an integration time-step. Each processor is only able to perform a certain amount of these time steps per unit of computation time. Using a larger integration time step allows the simulation to run faster and complete more steps in less computational time. However, if the time step is too large, it can cause the simulation to become unstable. This balance is highly constrained by the resolution and the speed at which the flow occurs (Courant condition), and in our case, time-step lies between 0.5 and 4s to be able to perform a 24-hour forecast in 2h.
- **Computational Resources**: High-resolution simulations demand significant computational power, including access to supercomputing facilities. However, resources are finite, and there is competition for computational time on shared systems. The maximum number of processors available on the CNRS supercomputing centre of the university of Corsica is 384. However we used only 150 to run our simulations.
- **Data Handling**: Managing large datasets poses challenges for data storage, transfer, and processing. Input data, such as high-resolution fuel maps, and output data, often exceeding 200 GB per simulation, require efficient handling mechanisms and to ensure that initial and boundary conditions are readily available in case of alert. It definitely requires an efficient file system attached to the supercomputer that can handle several hundred Terabytes as more than one computation can run and the other archived.

Given these constraints, optimising the computational performance of the model without sacrificing essential details was imperative. The necessity for rapid computation to support real-time decision-making drove the development of strategies to balance the trade-offs between model accuracy and computational efficiency.

2.3. Choice of the reference configurations

In order to find a reasonable trade-off between velocity and accuracy of the computations, we conducted a series of tests, experimenting with various configurations by modifying the number of nested grids, resolutions, and time steps. After an initial exploratory phase, we focused on three primary configurations: a non-nested setup, a two-level nested grid, and a three-level nested grid. Despite the varying spatial discretization, these three configurations have in common the dimension of the innermost domain (24x24 km), which is the domain coupled with ForeFire and where the wildfire is observed.

Our initial tests were conducted on five intense fires from the Portuguese fire database (Benali et al., 2023): Vila de Rei, Oliveira de Frades, Anadia, Arouca and Pedrógão Grande. These fires were chosen not only for their scale but also because they represented varied meteorological conditions, such as strong winds or established pyro-convection. For each case, we retrieved boundary conditions from the latest available forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF) just before the fire's ignition. Each simulation was initialised at the presumed point(s) of ignition and continued either until the end of the day or, in some cases, beyond one day.

During testing, several configurations produced physically unrealistic results due to numerical constraints. For example, certain resolutions were incompatible with the turbulence scheme, while overly steep orography created challenges in other setups. These issues, largely numerical, underscore the complexity of parameter optimization and demonstrate why some configurations are more viable than others.

In this report, we avoid delving into the detailed trial-and-error process required to make these adjustments, and instead, focus on the three most promising configurations, particularly those with two and three levels of nesting. These Configurations are summarised on Table 2.

Table 2: Main characteristics of the tested reference configurations.

Configuration Grid	Outer Size (X1)	Middle Size (X2)	Inner Size (X3)	Resolutions
Nested1	24 km	-	-	ΔX1 = ΔY1 =120 m
Nested2	120 km	24 km	-	ΔX2 = ΔY2 =160 m ΔX1 = ΔY1 = 800 m
Nested3	240 km	60 km	24 km	ΔX3 = ΔY3 = 80 m

				ΔX2 = ΔY2 = 400 m ΔX1 = ΔY1 = 2000 m

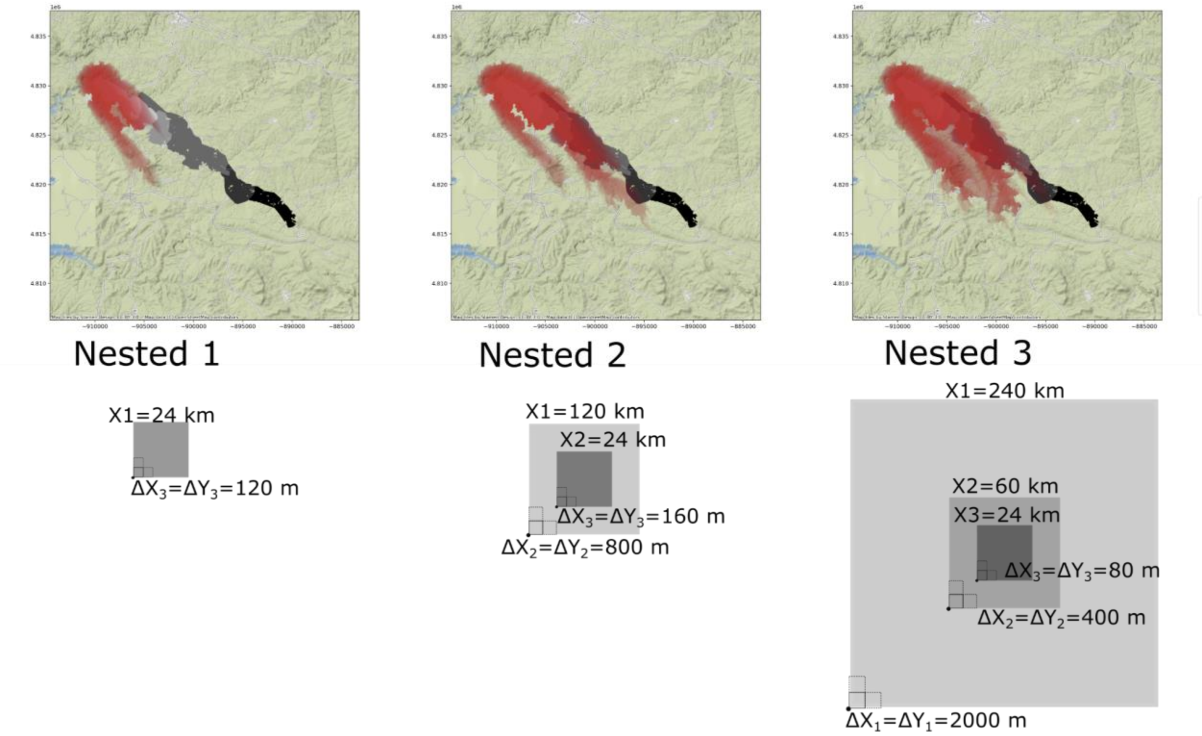


*Figure 3: Simulation of a real case fire using different configuration domains: not nested (Test1), nested 1 time (Test2) and nested 2 times (Test3). The upper figures show the fire progression in the innermost domain (simulated in shades of red versus real observed fire in shades of gray), while the bottom line gives a schematic structure of the nested configuration used. The simulation consisted in simulating 11 h of fire and calculation time on 150 Intel - 2*Xeon 6230R intel processors was respectively ~1h, ~4 h,~12 h (set-up phase excluded). Clearly TEST1 shows that using small domains, while faster, does not well interpolate the boundary conditions given by operational forecasts data. TEST 2 looks like a reasonable compromise between resolution, good initialization, simulation scale. Similar results were obtained on other real case fires.*

2.4. Computation results

The simplest single-nest configuration, 'Nested 1,' was quickly abandoned as it failed to produce satisfactory results. For example, in Figure 3, we compare the simulated wildfire perimeter with observations and note that this initial configuration shows the greatest discrepancy with observed data, whereas the other two configurations yield comparable and more accurate results—an outcome observed across multiple cases. This difference in behaviour is most likely due to the absence of an external domain which allows to properly interpolate the coarse boundary and initial conditions given by the operational forecast centres (9 km for ECMWF). By using an external, larger but lower resolution domain, MesoNH can exploit more of the ECMWF data and solve large scale meteorological patterns which are then fed to the lower resolution domain. This is important not only for a good representation of the evolution of local wind patterns but also for pyro-convection, which requires good modelling of the transport of moisture and water species brought in the simulation domain by larger scale meteorological patterns. In Figure 4 we illustrate a timeframe of the simulation of the Pedrógão Grande wildfire where the formation of a pyro-convective cloud is observed in the Nested 2 configuration (left) but not on the Nested 1 (right). Pyro-convective activity is observed even in greater detail in Nested 3, but at the expense of a much higher computational time (see Table 2).

We then focused on evaluating the two- and three-nest configurations, comparing their computational times across different fire cases. The results indicated that the three-nest configuration, especially for fires with intense pyro-convection, required prohibitively long computation times, making it impractical for most cases. Consequently, we selected the two-nest configuration as the optimal setup. This setup provided reasonable computational times and was consistent in terms of convection and smoke transport behaviour, aligning with the limited observational data available. These findings can be observed in the following figure and are also illustrated in the initial configuration presentation for the Vila de Rei case.

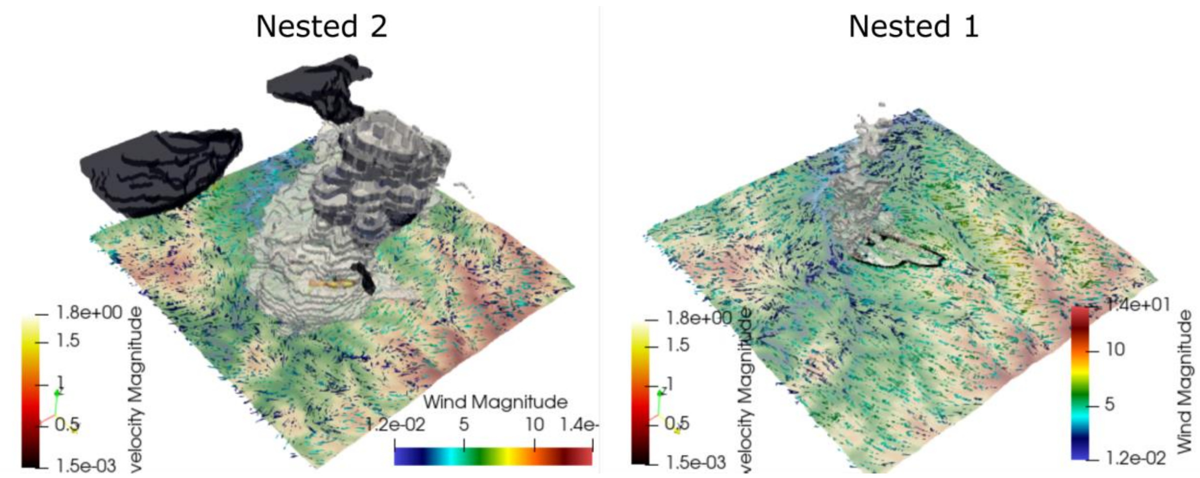
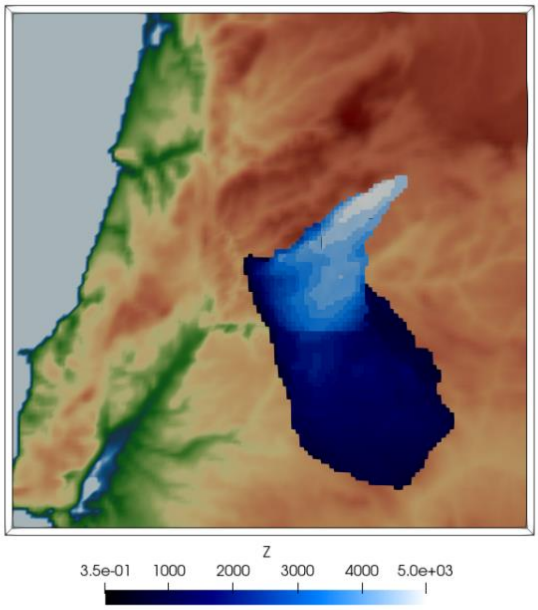


Figure 4:The same timeframe of the Pedrógão Grande simulation is showed for the Nested 2 (left) and Nested 3 (right) configuration. Formation of a Pyro-convective cloud is observed only in Nested2 and results in a noticeable acceleration of the fire front.



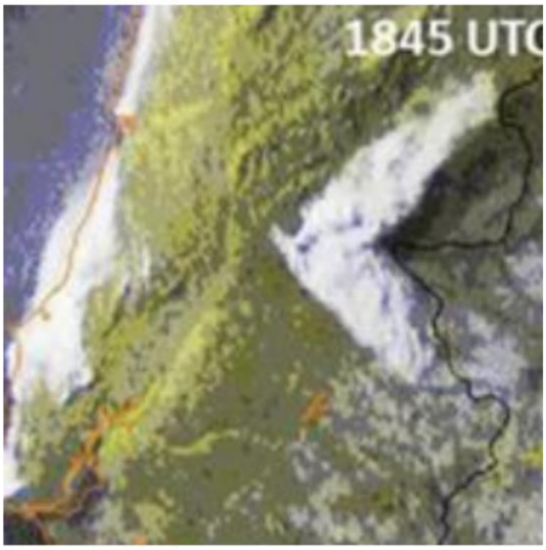


Figure 5: Smoke plume height (left) and satellite observation(right) for the Nested 2 parameterisation, Vila del Rei Fire.

Computation times on the university HPC machine (150 Intel - 2*Xeon 6230R intel processors used in the simulations) are provided in the table below:

Table 3: Summary of simulated wildfire cases. The simulated hours are reported along the required simulation times in the Nested 2 and Nested 3 configurations.

Test Case Name	Simulated Wildfire Hours	Nested Configuration
Vila del Rei	11 h	**NESTED 3:** ~ 11 h
		NESTED 2: ~ 3 h
Oliveira Frades	12 h	**NESTED 3:** ~ 10:30 h
		NESTED 2: ~ 2:30 h
Anadia	26 h	**NESTED 3:** ~ 22:40 h
		NESTED 2: ~ 2:30 h
Arouca	30 h	**NESTED 3:** ~ 51 h
		NESTED 2: ~ 2:40 h
Pedrógão Grande	17 h	**NESTED 3:** ~ 16 h
		NESTED 2: ~ 2:20 h

2.5. General considerations and conclusion

We remark that an in-depth discussion of the aforementioned cases along with a detailed comparison with available observations was beyond the goal of this study. Such an effort was made for the Pedrógão Grande case (Couto et al., 2024a), and many others are in preparation at the time this report is being written. Given the project's limited timeframe, our primary focus was on developing a functional system capable of producing operationally viable results. With the support of automated code and preconfigured routines, we successfully established a baseline simulation system, creating a "zero state" from which more comprehensive studies can be launched in the future. This foundation enables future research to enhance parameterization and computational efficiency, ultimately refining the model to meet the precision requirements necessary for improved fire behaviour forecasting and smoke transport modelling.

3. Automation of the Forecasting Chain

3.1. Data Acquisition and Integration

The process begins with the acquisition and integration of various input data critical for running the coupled fire-atmosphere models, run the models, and generate a compiled files as described by the schema in Figure 6:

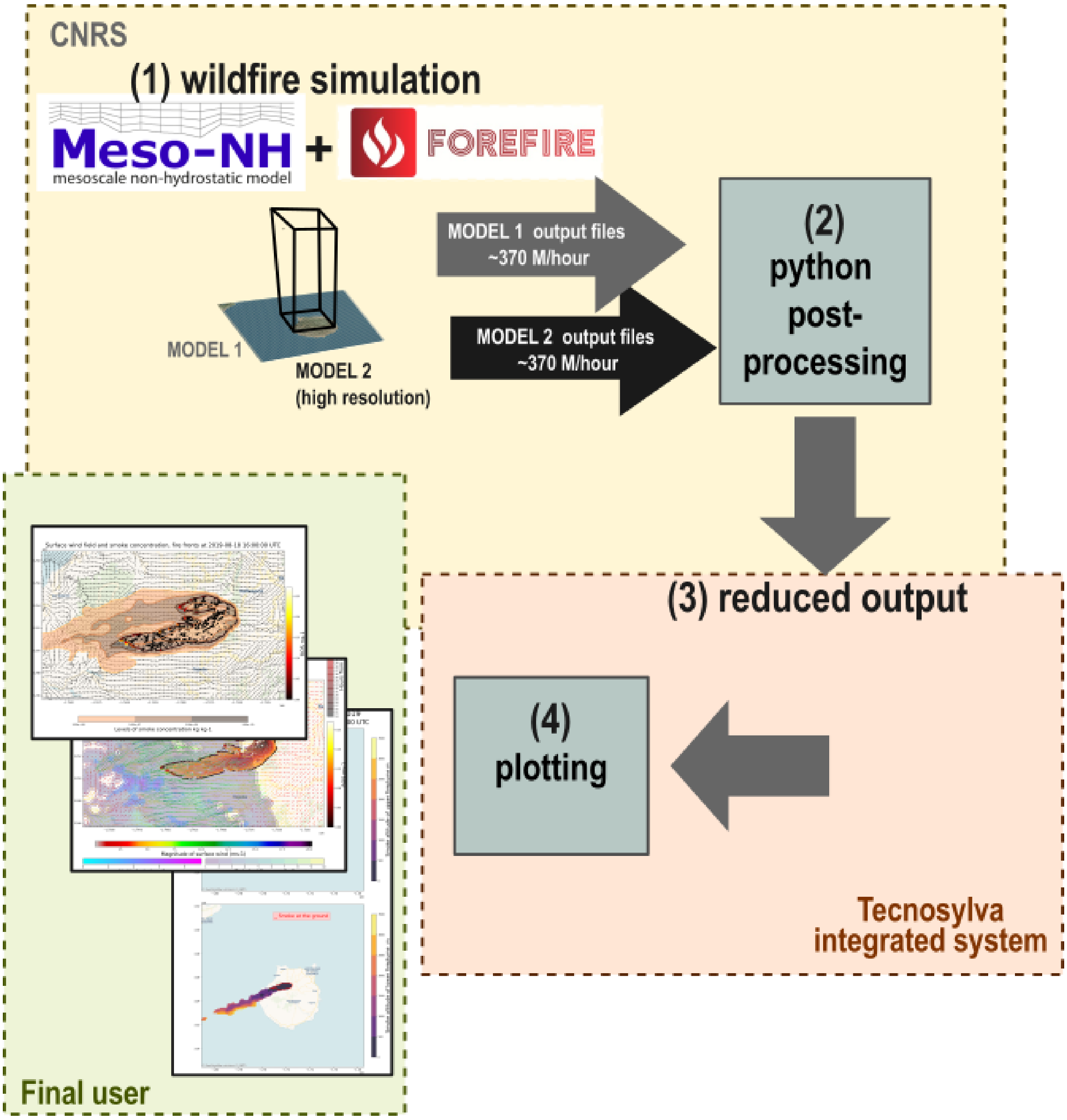


Figure 6: Schematic illustration of the targeted workflow.

The primary sources of input data include:

- **Fire Alerts**: Information about fire ignitions, such as GPS coordinates, ignition times, and initial perimeters. These alerts are obtained from operational fire

services, satellite detections, or monitoring systems. For instance, ignition data may include a list of ignition points with associated timestamps, specifying where and when the fire started.
- **Meteorological Data**: High-resolution weather forecasts and atmospheric data are sourced from the European Centre for Medium-Range Weather Forecasts (**ECMWF**). This data (as GRIB files) provides the necessary atmospheric conditions for initialising and driving the atmospheric model components (MesoNH). Automated requests are formulated to retrieve meteorological data for the specific spatial and temporal domains relevant to the simulation.
- **Fuel Models**: Detailed information about vegetation and fuel types is crucial for accurately modelling fire spread. Fuel maps are generated by processing land cover datasets, such as the **ESA WorldCover 10m 2021** or **S2GLC Europe 2017** products. These datasets are processed to classify land cover types into fuel categories required by the ForeFire model.

To automate data retrieval and preprocessing steps, scripts are developed to interface with data repositories and perform necessary transformations. For example, the scripts handle tasks like:

- Downloading meteorological data from ECMWF based on specified coordinates and time ranges using ECMWF's MARS python library.
- Extracting and processing land cover data to generate high-resolution fuel maps.
- Converting coordinate systems and reprojecting datasets to ensure compatibility between different data sources.

Ensuring data quality and consistency across different regions is achieved by implementing validation checks within the automation scripts. These checks verify that:

- All required data files are present and accessible.
- Data formats are consistent and conform to expected standards.
- Spatial and temporal resolutions are appropriate for the simulation scales.
- No gaps or discrepancies exist in the input data that could affect simulation accuracy.

3.2. Development of Automation Scripts

The scripts are primarily written in **Python**, leveraging its extensive libraries for data processing and scientific computing. Overall, it has about **80.000 new lines of code** covering all aspects of data retrieval, pre-processing, processing and post-processing. For deeper details and reproducibility, all codes are available online at https://github.com/forefireAPI/firefront/tree/master/tools. This report will not cover these scripting procedures in detail; for further information, please refer to the GitHub repository, where detailed descriptions are provided in the comments within the Python modules.

Purpose and Functionality of the Scripts

The scripts serve multiple functions:

- **Case Generation**: Automate the creation of simulation cases based on input parameters such as ignition locations, dates, and desired simulation durations. They generate configuration files and directory structures needed for running the simulations.
- **Data Retrieval and Preprocessing**: Automate the downloading and processing of meteorological and land cover data. This includes interfacing with ECMWF APIs for weather data and processing satellite-derived land cover datasets to create fuel maps.
- **Model Initialization and Execution**: Set up the MesoNH atmospheric model and the ForeFire fire propagation model, configuring nested domains and model parameters. The scripts manage the execution sequence, ensuring that dependencies between models are correctly handled.
- **Post-processing**: Automate the extraction and conversion of raw simulation outputs into formats suitable for analysis and visualization, such as NetCDF, VTK, and KML files.

Workflow of the Automated Forecasting Chain

The automated forecasting chain follows these steps:

1. **Input Specification**: Users provide essential input parameters, including ignition coordinates (`latitude`, `longitude`), ignition times, simulation start and end times, and desired resolutions for nested domains.
2. **Case Setup**: Scripts generate the simulation case directory and populate it with necessary templates and configuration files. They calculate domain extents, nesting levels, and time steps based on input parameters.
3. **Data Acquisition**: Meteorological data is automatically requested from ECMWF, and land cover data is processed to generate fuel maps at the required resolution.
4. **Model Initialization**: The MesoNH and ForeFire models are configured using the prepared input data. Nested domains are established, and boundary conditions are set up using the retrieved meteorological data.
5. **Simulation Execution**: The scripts initiate the simulations, managing the execution of different model components. They handle the sequencing of atmospheric and fire models.
6. **Post-processing and Output Generation**: Upon simulation completion, scripts process the output data to extract relevant variables and generate graphical representations.

4. Case Studies and Development of Output Tools/Files

4.1. Overview of Partnerships with Operational Fire Services

To ensure the practical applicability of our coupled fire-atmosphere modelling platform, we engaged in collaborative efforts with operational fire services (LLs), in three key regions:

- **Canary Islands (Spain)**
- **Portugal**
- **Landes de Gascogne (Aquitaine, France)**

These regions were selected due to their history of extreme wildfire events and the availability of operational services willing to participate in collaborative research.

Objectives and Methodologies of the Collaborative Efforts

The primary objectives of collaborating with the Living Labs were to:

- **Identify Significant Wildfire Events**: Work with local fire services to select past extreme wildfire events suitable for re-analysis and model validation.
- **Gather Operational Insights**: Obtain detailed information about the selected fires, including ignition points, fire progression data, and any observed atmospheric phenomena.
- **Validate and Refine Models**: Use real-world data to validate the accuracy of our simulations and adjust model parameters accordingly.
- **Develop User-Centric Outputs**: Understand the specific information needs of operational personnel to tailor our simulation outputs for practical use in decision-making.

Methodologically, the collaboration involved regular communication with the Living Labs, including meetings, data exchanges, and iterative feedback on simulation results and output formats. The three selected wildfire were:

- 11/07/2020 wildfire in Riodades (LL Portugal)
- 12/07/2022 Teste-de-Buch wildfire (LL Aquitaine)
- 17/08/2019 wildfire in Valleseco (LL Gran Canaria)

The three cases are presented thereafter, on the basis of the reports made for each LL with intermediate images displaying the quest for the best possible representation in operations and which have been here slightly readjusted. Including these partial reports intends to display the efforts made during the LL interactions.

4.2. Simulation of the 11/07/2020 Wildfire in Riodades (São João da Pesqueira), Portugal

In this brief report we present the main features of the numerical simulation which we run to study the propagation of the 11/07/2021 Riodades wildfire. The main purpose of this concise document was to share sample images of the results obtained and to start a dialogue with the LL regarding the types of figures or graphs that would be most beneficial. This is necessary as the simulation produces a great amount of data and an effective visualisation is not straightforward. We start with a general overview of the simulation setup (which may be changed in the future) and then we present briefly observed results. However, we would like to focus attention to the Figures 11 to 14 where we illustrate some of the available data and some possible forms of visualisation. Concerning the simulation setup, we use the numerical weather prediction code Meso-NH coupled with the wildfire spread code ForeFire. The initial and boundary conditions are interpolated using the atmospheric fields of the day considered obtained from ECMWF. The total simulation domain spans 120 km, with a finer grid resolution (160 m) in a 12 km area around the ignition point, and 800 m elsewhere (see Figure 1). The simulation starts at 12:00 UTC and ends at 24:00 UTC, time at which the simulated fire exits the inner domain.

Figure 7: Nested domains used in the simulation.

In Figure 2 we show the fire progression as predicted by the simulation compared with the available observations. We note that the simulated fire follows the observed propagation direction during the first two hours of ignition (between 14:00 and 16:00 local time, 13:00 - 15:00 UTC), but with respect to the actual fire, the burning area extends to the east.

At 16:30 UTC this extension is more pronounced and, compared with the observations, we remark a change of direction in the surface wind from north-easterly to north-westerly. This change in the direction of propagation is present also in the observations, but happens later in time (after 18:00 UTC).

Considering this, at 20:30 UTC, the simulated burned area is significantly larger and extends more to the east. It would be interesting to understand if this difference is due only to the many uncertainties present in the numerical simulation (boundary conditions, used fuel map and Rate Of Spread model among others) or if there has been an early intervention of firefighters in the east side of the fire.

This north-westerly wind continues up to about 21:00 UTC. Then the wind changes again to north-easterly in agreement with the observations which display a propagation in this direction after 21:30 UTC (not shown in Figure 8)

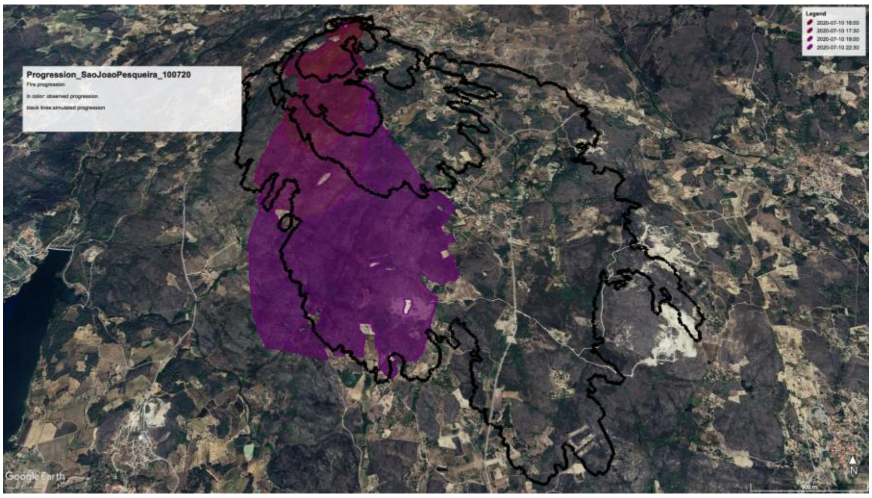


Figure 8: Observed propagation of the wildfire (in colour) with the corresponding fronts obtained in the simulation (thick black lines) The legend is in local time.

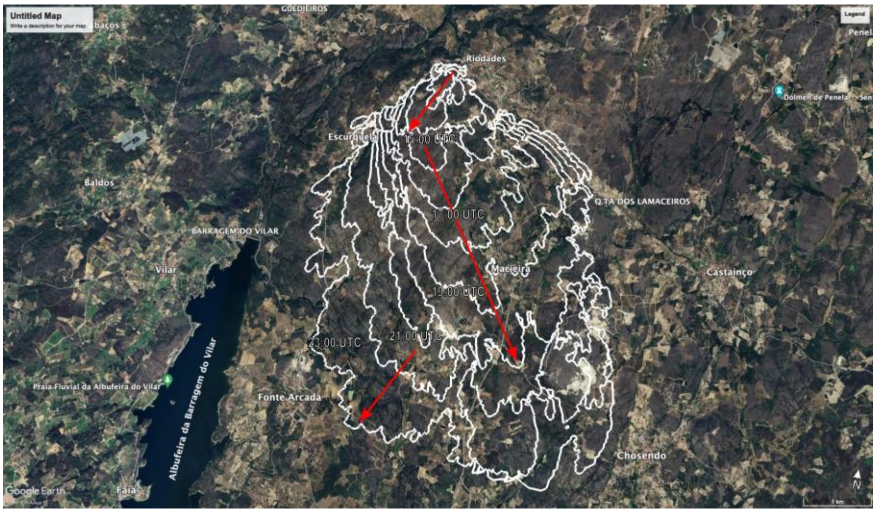


Figure 9: Simulated wildfire front (thick white contours). The time between the displayed contours is 1 h. The arrows highlight the main changes in the propagation direction.

In Figure 9 we show the propagation of the wildfire as described by the numerical simulation (a contour for every hour). The arrows highlight the main changes in the propagation direction described above. We observe an acceleration of propagation to the east and south-west at approximately 17:00, then a new acceleration in the west starting at 22:00 UTC. In Figure 10 we show the map of the Rate Of Spread (Yellow is higher), which highlights what is described above.

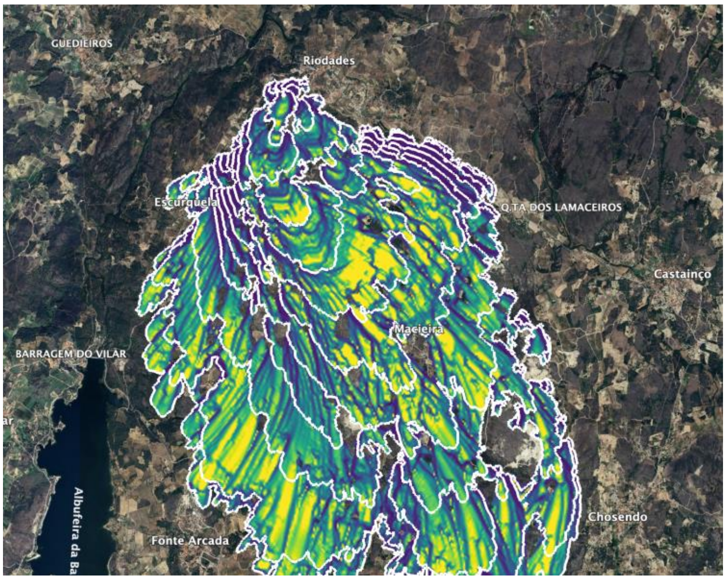


Figure 10: Rate of Spread (yellow=high, blue=low) of the simulated fire.

The numerical simulation allows one to study the atmospheric conditions surrounding the fire (the impact of the heat released from the fire on the local atmospheric conditions is also taken into account). All the meteorological variables (wind, temperature, water-species) are calculated explicitly.

These fields are solved in more detail in the smaller 12 km x 12 km domain surrounding the fire. In Figure 11 we show the surface wind (coloured arrows) at different times of the simulations, while in Figure 12 we highlight the regions of high turbulence surrounding the fire (in black) and the wind field within. In both figures the simulated fronts are illustrated with thick black lines and vertices with higher velocities are highlighted with larger points.

From the beginning of the simulation (12:00 UTC) up to approximately 17:00 UTC the local environment is characterised by high turbulence and convective cells with relatively strong vertical winds. The surface wind is overall northerly but otherwise there is not predominant easterly or westerly direction. The fire ignites and develops under such conditions and spreads along the slope of the hill (Figure 11.a). Around 17:00 UTC a northwesterly wind enters the domain, moving the turbulent region eastward and pushing the fire in this direction (Figures 11.b and 12.b). Then the surface wind slows down and changes smoothly from northwesterly to northeasterly (Figure 11.c).

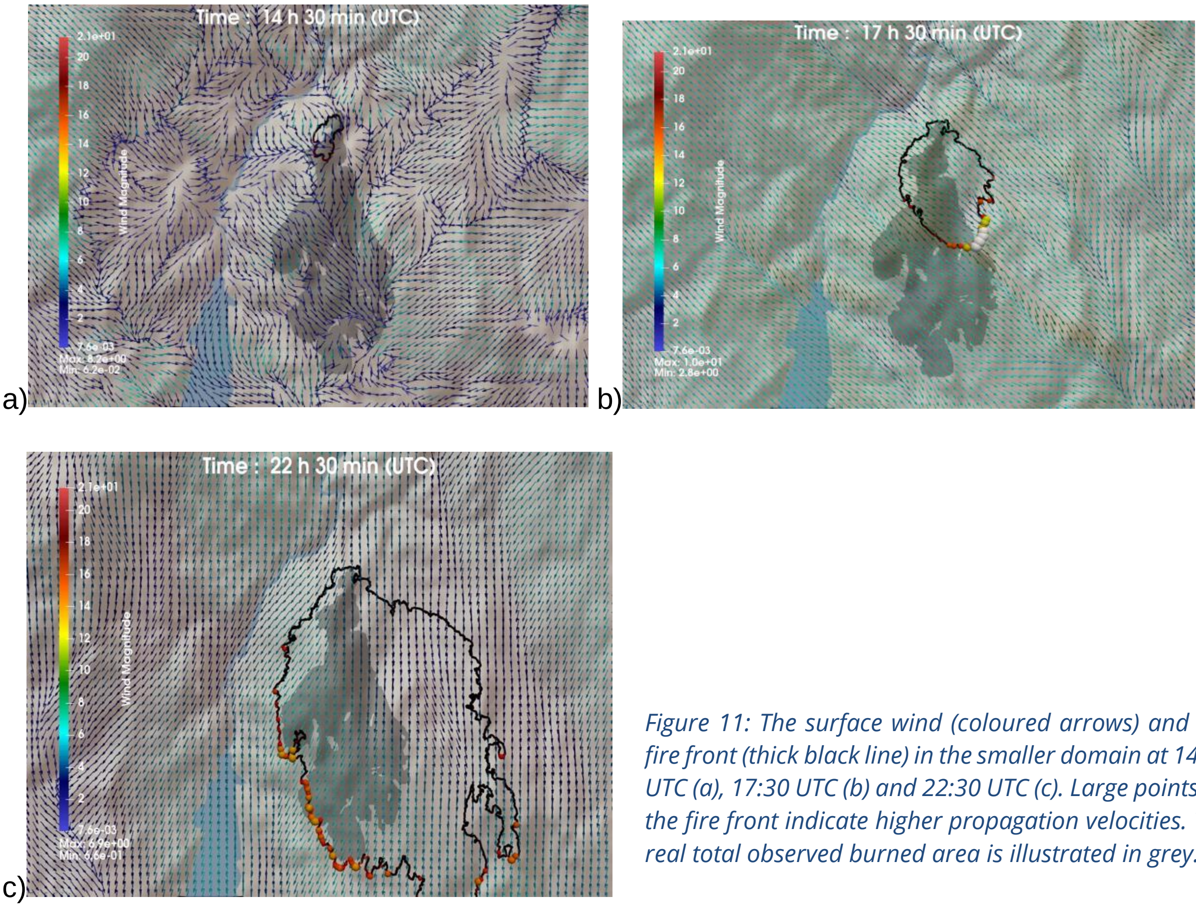
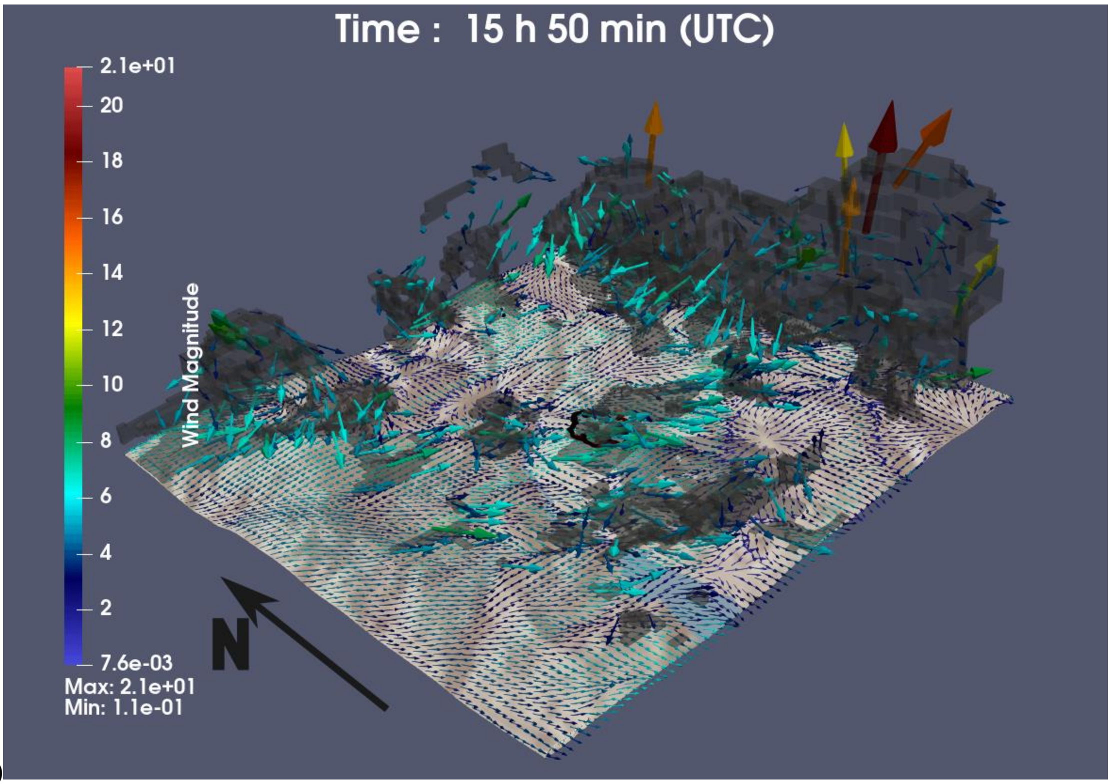
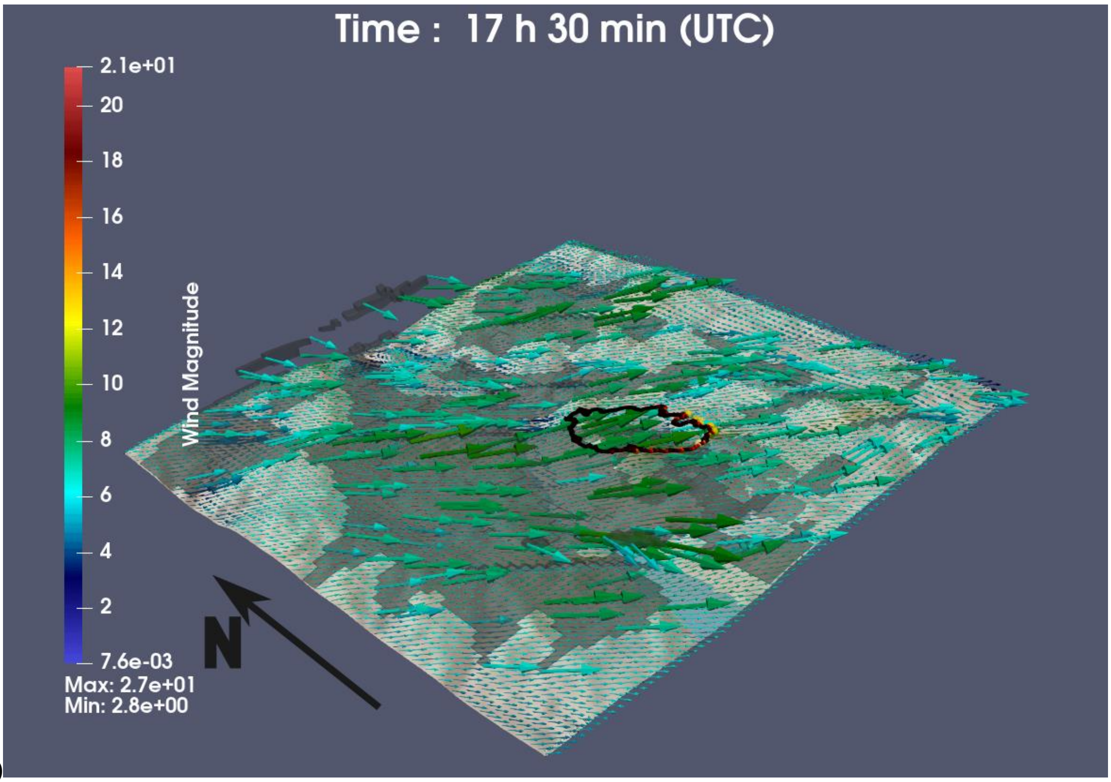


Figure 11: The surface wind (coloured arrows) and the fire front (thick black line) in the smaller domain at 14:30 UTC (a), 17:30 UTC (b) and 22:30 UTC (c). Large points on the fire front indicate higher propagation velocities. The real total observed burned area is illustrated in grey.



a)



b)

Figure 12: Regions of high turbulence are shown in dark grey along with the inner wind fields.

A smoke tracer is emitted from the burning regions into the atmosphere to track the development of the smoke plume. An early phase of the plume development is illustrated in Figure 13 while in Figure 14 we illustrate the global shape of the plume at 18:00 UTC. The colour scale indicates the altitude reached by the tracer.

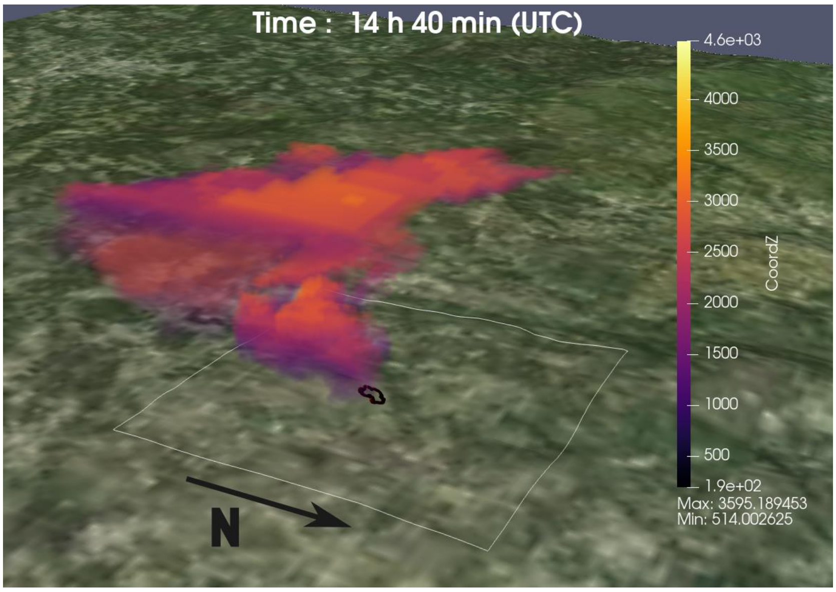


Figure 13: Early development of the fire plume, the color scale indicates the plume altitude

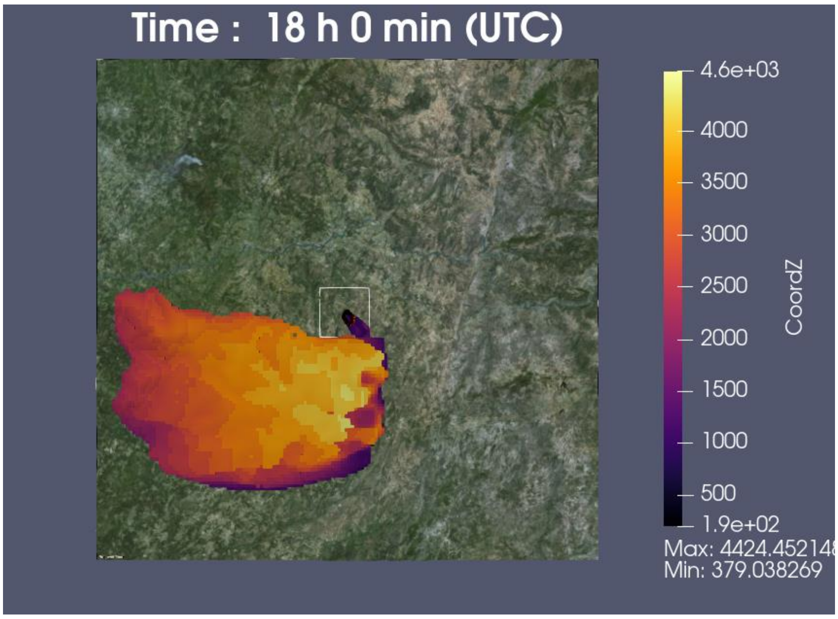


Figure 14: Global shape of the fireplume at 18:00 UTC. The colour scale indicates the plume elevation.

4.3. Numerical Simulation of the 12/07/2022 Teste-de-Buch Wildfire (Aquitaine, France)

In this report, we present the main characteristics of the numerical simulation we conducted to study the spread of the La Teste de Buch wildfire, which began on 07/12/2022.

The presented numerical simulation illustrates fire behaviour over 24 hours starting from 12:00 UTC (14:00 local time). Two nested domains, as shown in Figure 15, were used with respective resolutions of 800 m and 160 m. The inner domain (higher resolution) measures a total of 24 km, while the outer domain measures 240 km. The fire perimeter is fully contained within the inner domain and is simulated using a fire propagation model with higher resolution to account for obstacles such as roads and various types of fuels in greater detail. The heat and vapour released by the fire are then injected into the meteorological solver (with a resolution of 160 m in the inner domain), while the wind field calculated by the meteorological solver is used to propagate the fire. The meteorological solver uses ECMWF forecast data for the given day as initial and boundary conditions. The ignition point is located at coordinates: lat=44.581940, lon=-1.169495, with the fire declared at 12:30 UTC (14:30 local time). With this setup and running on 150 Intel cores on the HPC of the university of Corsica, the simulation duration was approximately 5 hours.

The simulation details (domain size, resolution, simulated time) can easily be adjusted in the future. We remark that the main purpose of this brief report is to illustrate the results and data available that our coupled approach can provide.

Figure 15: Domains used for the simulation. The inner domain has a higher resolution and is coupled with a fire propagation code.

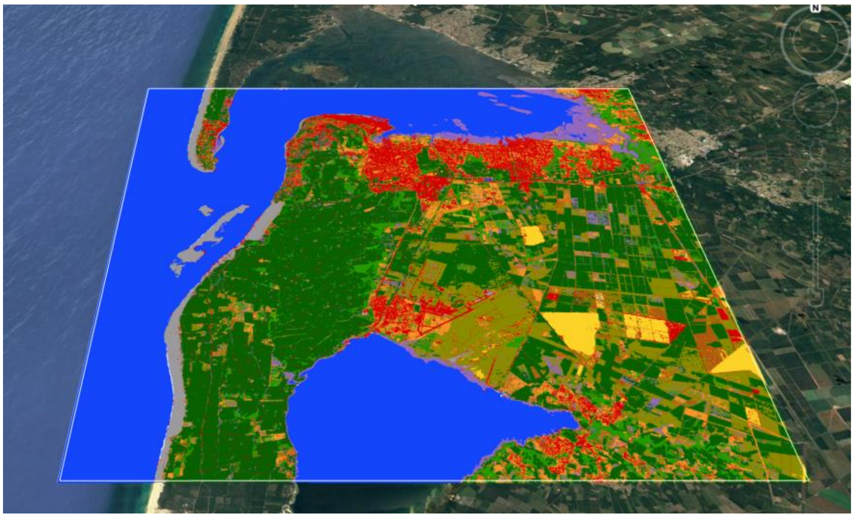


Figure 16: Fuel map used by the fire propagation code.

Results and Discussion

In the following, we briefly discuss the behaviour of the La Teste-de-Buch wildfire and the meteorological conditions characterising the first 24 hours of the fire, as illustrated by our numerical simulations. The figures provided, particularly starting from Figure 5, give an idea of the types of meteorological variables available from the simulation.

We begin by presenting the fire fronts, allowing us to generally discuss the observed behaviour during propagation. In Figure 3, we show the fire fronts from 13:00 UTC on 07/12 to 12:00 UTC on 07/13, with each front separated by an hour. In gray, we show the fire contour at 12:30 UTC on 07/13 as provided by Aquitaine LL. In Figure 19, we present a colour scale proportional to the fire's propagation speed. We observed rapid propagation following a northeast wind from the start of the fire until about 01:30 UTC on the morning of the following day. Afterward, the fire spreads more slowly without following any particular direction.

Figure 17 :Propagation of the fire from 12:30 UTC 12/07 to 12:00 UTC 13/07. Fire fronts are shown in white with frequency of 1 hour, the observed burning region is illustrated in grey.

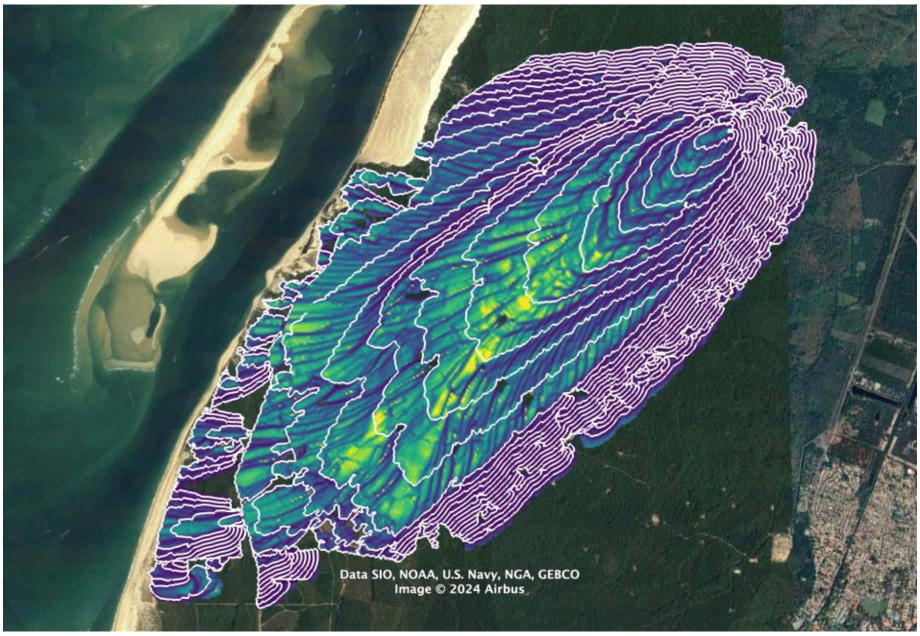


Figure 18: Fire propagation is illustrated using a color map proportional to the velocity of propagation (yellow=high, blue=low).

In Figure 19, we illustrate the surface wind field along with the fire fronts, while the actual burned area is shown in grey. The size of the points composing the front is proportional to the propagation speed. We show four different moments in time to provide an overview of the wind evolution during the simulation. A video illustrating the complete sequence with a 10-minute frequency is also available. At the beginning of the simulation, the surface wind is primarily from the northeast, but we observe some local inhomogeneities and the presence of turbulence near the ground (Figure 19.a). Around 18:00 UTC, the wind field becomes more homogeneous and continues to blow in a northeast direction (Figure 19.b). It then gradually shifts to an east wind (Figure 19.c) until around 09:00 UTC (Figure 19.c), when we again observe an inhomogeneous wind field near the ground.

The simulations also allow to study the development of the fire plume. In Figure 20, we show the fire plume as observed a few hours after the start of the fire and at the end of the simulation. Information regarding the altitude reached by the plume and its small-scale structure is also available. In Figure 21, we show a close-up view of the plume (nested domain) and areas where turbulent flow is observed. A vertical view of the wind field surrounding the plume is provided in the cross-section shown in Figure 22, where the colour scale indicates the vertical wind speed.

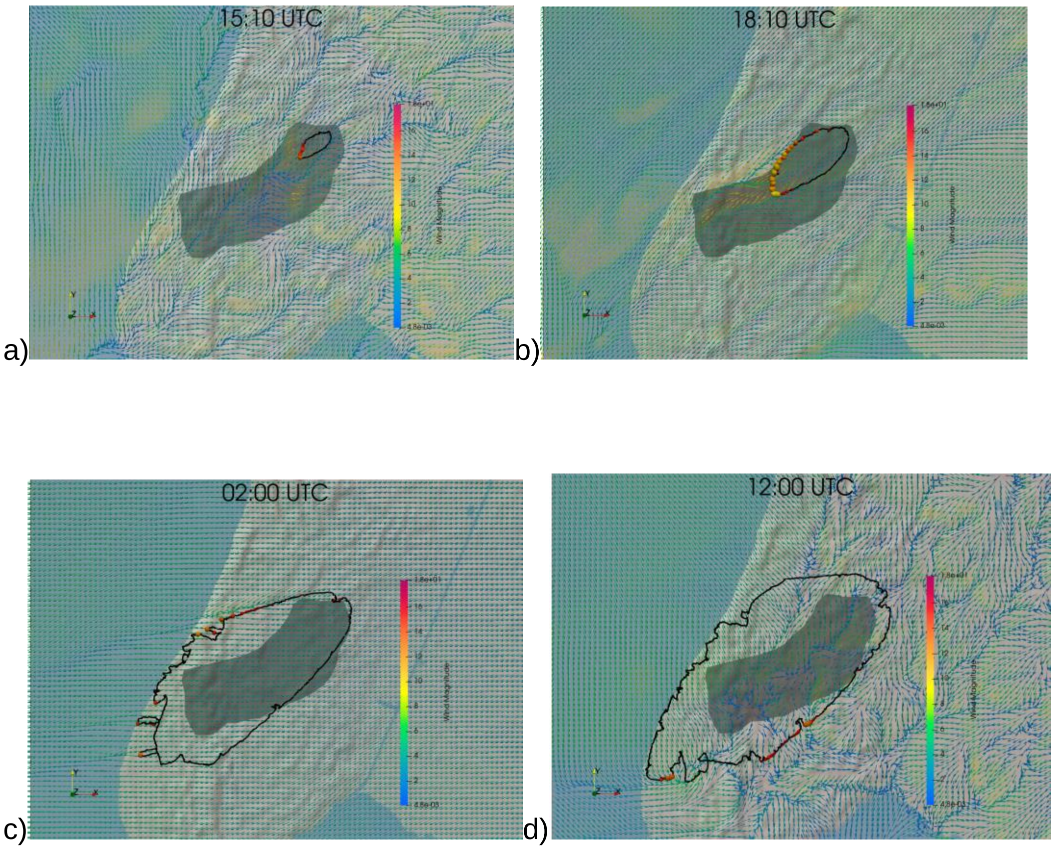


Figure 19: Surface wind and wildfire front at 15h10 UTC (12/07), 18h10 UTC (12/07), 02h00 UTC (13/07), and 12h00 UTC (13/07).

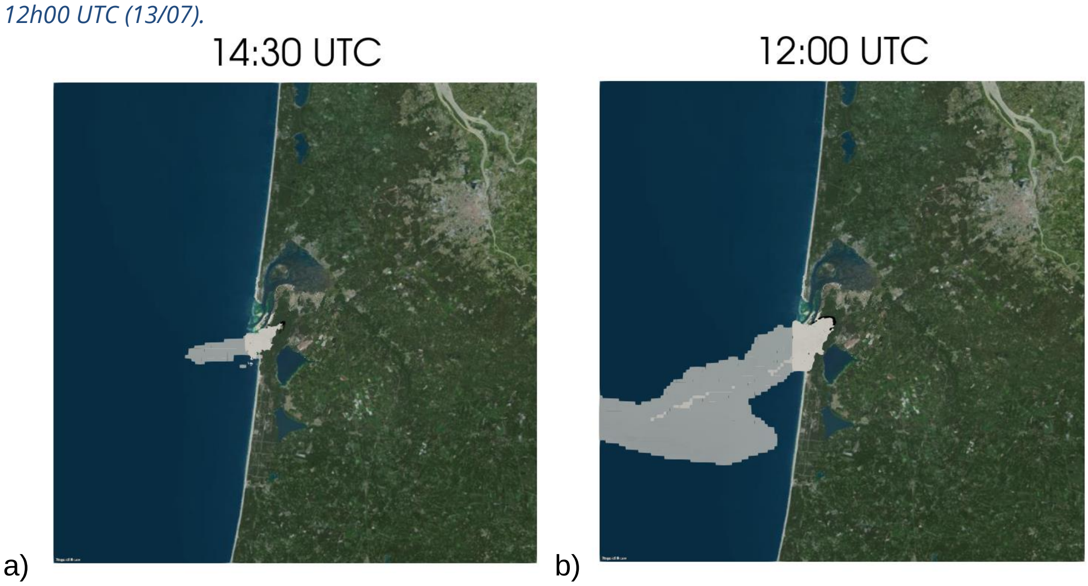


Figure 20: Fire plume 2 hours after the start of the fire (top) and at the end of the simulation (bottom).

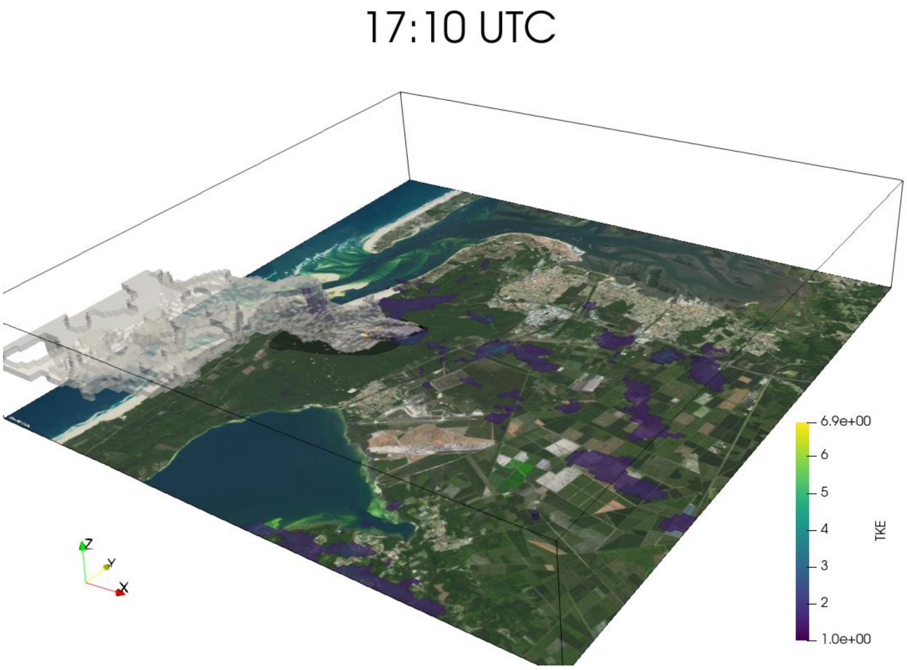


Figure 21: Close-up view of the fire plume and areas of turbulent flow.

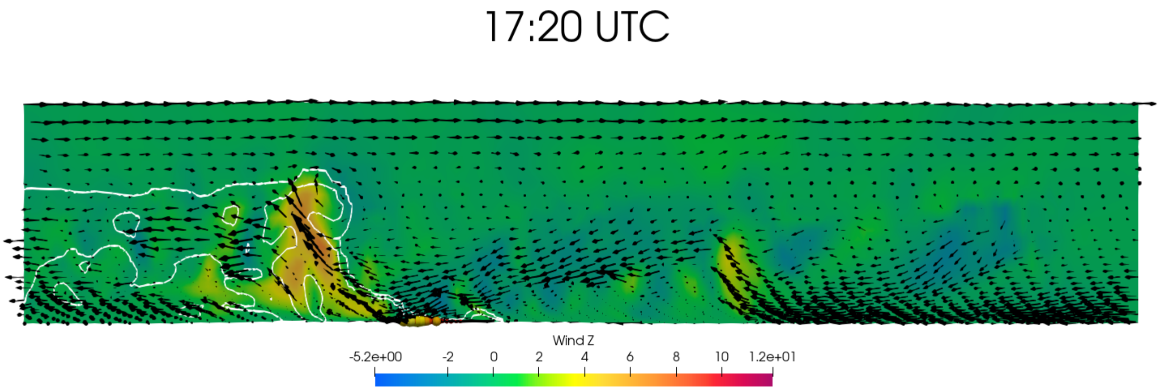


Figure 22: Vertical section showing the contours of the fire plume (in white) and the wind field. The colour scale indicates the vertical component of wind speed..

4.4. Numerical simulation of the 17/08/2019 wildfire in Valleseco (Gran Canaria)

Here we present the main features and the main results of the numerical simulation we performed for the case of study of the Valleseco wildfire, which affected the island of Gran Canaria between the 17th and the 21th of August 2019 and resulted in approximately 10 000 burned hectares.

The Valleseco wildfire started in the afternoon of the 17/08/2019 at 14:47 UTC (15:47 local time) and was finally mastered only some days later, on the 22/08. The fire spread to the west and burned approximately 10 000 ha in total. Figure 23 illustrates the fire final perimeter and the ignition point as provided by the LL. Concerning the progression of the fire, satellite images from the NASA Worldview application suggest a rapid expansion to the west between the 17th and the 18th of august and the persistence of a significant fire activity during the 19th. Then the fire loses progressively its strength and is finally extinguished on August 22 (Figure 24).

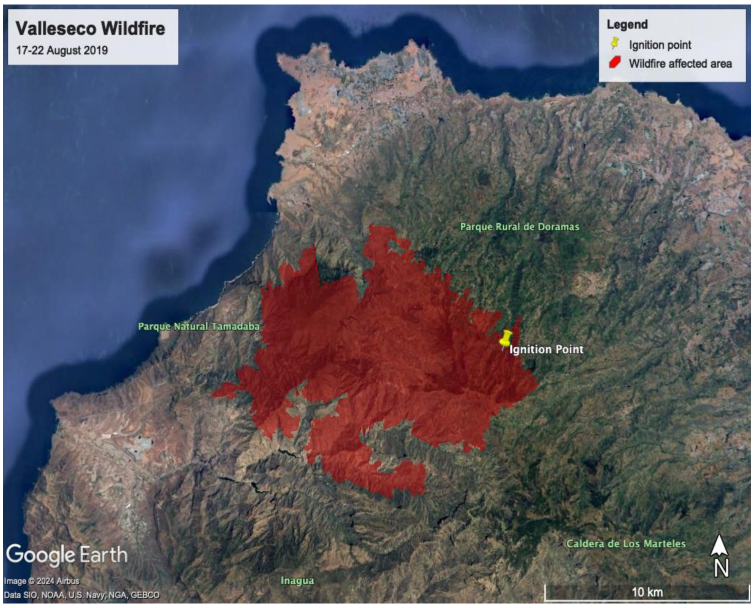


Figure 23: Total area affected by the fire along with the ignition point.

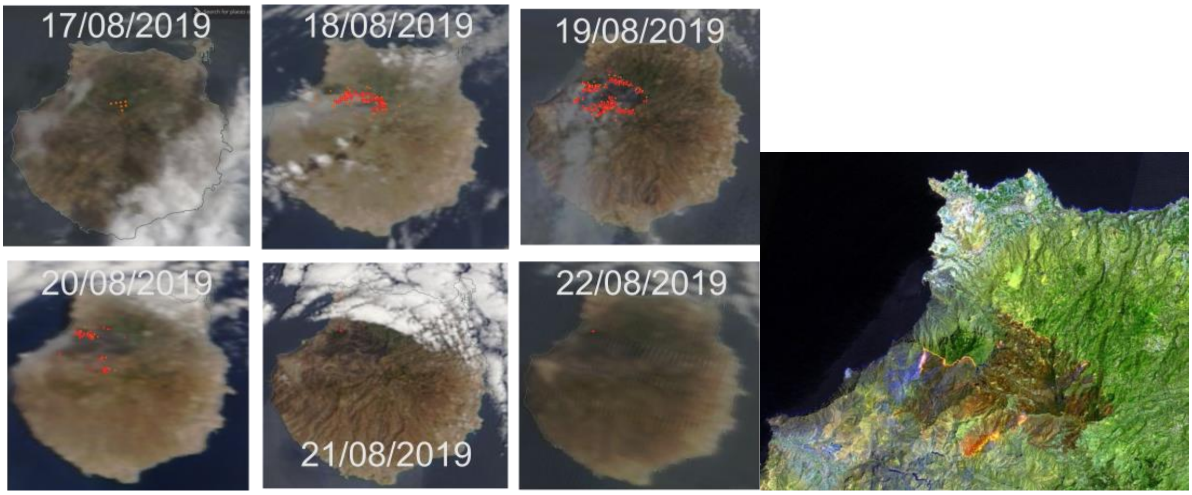


Figure 24: On the left the images taken from the NASA worldview application illustrate the thermal anomalies registered by different satellites (Terra and Aqua MODIS and Suomi NPP VIIRS). On the left we show a color modified image from the Copernicus emergency service taken on august 19th, which allows us to observe the most active fire fronts on that day (available on Wikipedia).

The numerical simulation involves the use of an atmospheric solver which simulates local meteorology coupled with a fire propagation code. To account for the actual atmospheric conditions, the meteorological solver uses forecast data from operational weather forecasts services as initial and boundary conditions. In this simulation, we used ECMWF forecasts data updated with a frequency of 3 h. The numerical set-up of the simulation involves two nested domains with respective resolutions of 800 metres and 160 metres, as shown in Figure 4. The inner domain (higher resolution) measures a total of 24 kilometres, while the outer domain measures 240 kilometres. The use of an external, coarser domain is important to use in a more relevant way the boundary condition given by the meteorological data from ECMWF, whose resolution is not very high. Moreover, the use of a larger simulation domain allows to simulate the dispersion of the fireplume on a larger scale. The fire perimeter is entirely contained within the inner domain and is simulated through a fire propagation model that has a higher resolution than the atmospheric model (10 m to account for obstacles such as roads and different types of fuels in more detail). The heat and vapour released by the fire are then injected into the meteorological solver (which has a resolution of 160 metres in the inner domain), while the wind field calculated by the meteorological solver is used to propagate the fire. The ignition point is located at coordinates: lat=28.034118, lon=-15.593972, while the fire propagation is started at 2019-08-17 14:50:00 UTC (15:50 local time). For the fuel map, we used the data of the ESA Worldcover 2021, which has a resolution of 10 m while we used the Rothermel model for the propagation of the fire front. In total, we simulated 33 hours starting from 2019-08-17 12:00:00 UTC up to 2019-08-18 21:00:00 UTC. With this configuration, the simulation needed 9:30 hours to complete, using 150 intel cores.

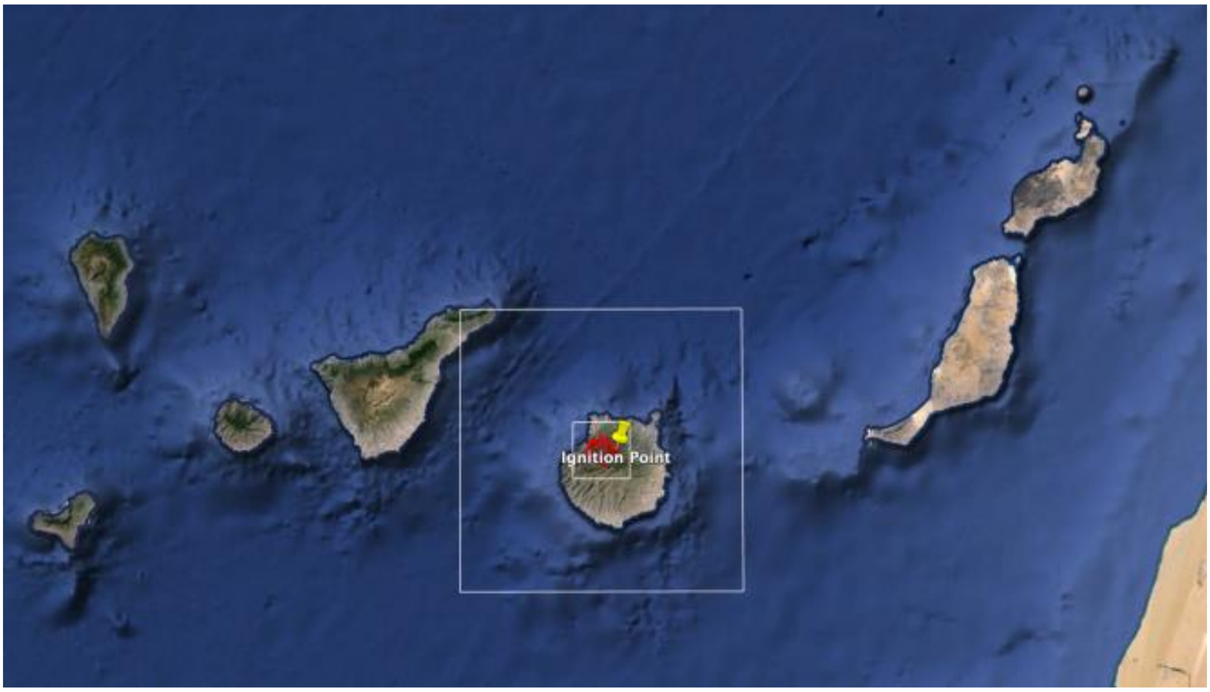


Figure 25: The nested domains used in the simulation are illustrated with white contours.

Simulation Results

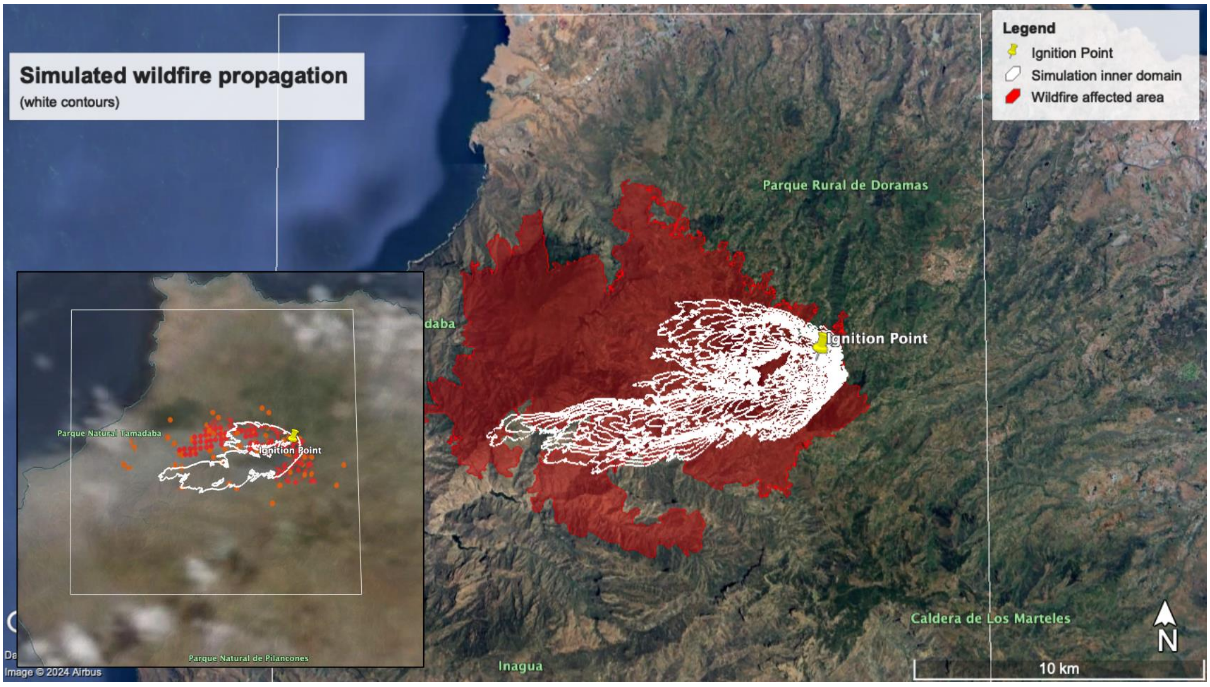


Figure 26: The total observed fire region (in red) is compared to the simulated fire propagation (white contours) which has been stopped at 2019-08-18 21:00:00 UTC. In the inset on the left, the simulated fire fronts are compared with the satellite observations in date 2019-08-18.

In Figure 26, we illustrate the fire evolution from 2019-08-17 12:00:00 UTC up to 2019-08-18 21:00:00 UTC. The observed fire affected area is illustrated in red, while we show in white the simulated fire fronts, with a frequency of an hour. The fire propagates slowly during the first hours following ignition, but undergoes a fast acceleration during the early hours of 18/08. At 2019-08-18 21:00:00 UTC, the simulated fire perimeter is mostly contained within the observed burned region, but its main propagating front is more in the south compared with the main active region during the day 2019-08-18, when the fire was reported to reach the Tamadaba Natural Park (see also the comparison with the satellite image in Figure 26).

The surface wind field surrounding the ignition site and the fire propagating region is illustrated in Figure 27 for some chosen times of the simulation (this type of output is available with a frequency of 10 min). The region is dominated by an easterly wind which presents different magnitudes along the various valleys and slopes characterising the region. The fire evolves to the west following this partly inhomogeneous wind field. In Figure 27, the surface wind field is illustrated with coloured arrows while the fire fronts are shown with points whose size is proportional to the propagation velocity. Within the fronts, the burned area is colour shaded as a function of the burning time. In Figure 28 we present a similar view where we illustrate varying intensity regions of smoke concentration at the ground for the same UTC times displayed in Figure 27. A detailed image of the plume taking a different 3D view is displayed in Figure 9 for 2019-08-18 13:30:00 UTC, where we colour code the plume to highlight its maximum altitude. Two sections of the plume (shown in the lower part of the picture) illustrate the vertical wind velocity and the turbulent energy within the plume and in the surrounding region. The direction of the wind field is also displayed with arrows within the section.

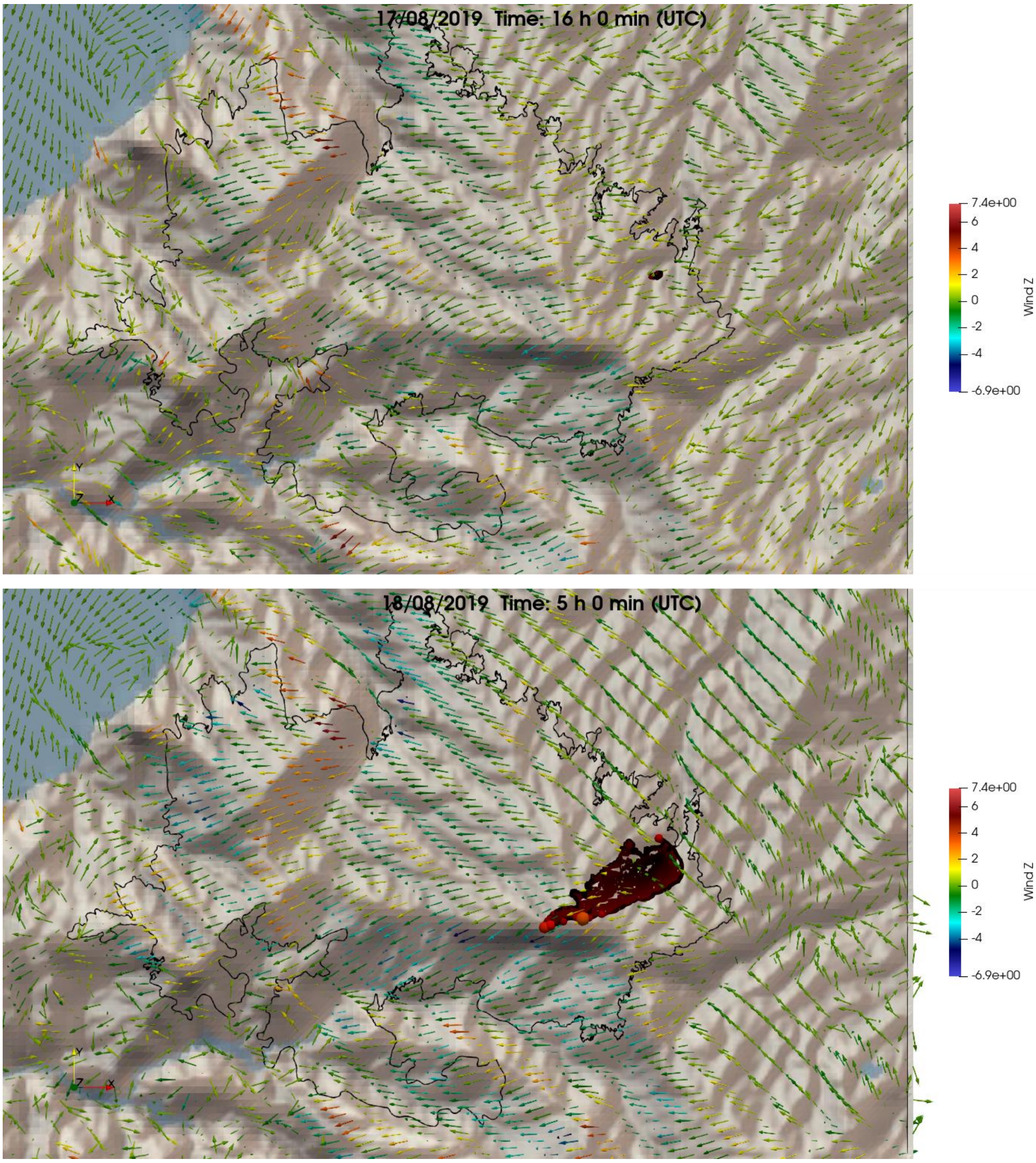


Figure 27: Surface wind field (coloured arrows) along with the propagating fire fronts (illustrated with dots whose size is proportional to the propagation speed. The simulated burned area within the fronts is colour coded by time of burning. The illustrated snapshot refers to 2019-08-17 16:00:00 UTC and 2019-08-18 05:00:00 UTC. The fine black contour shows the total burned observed area for comparison.

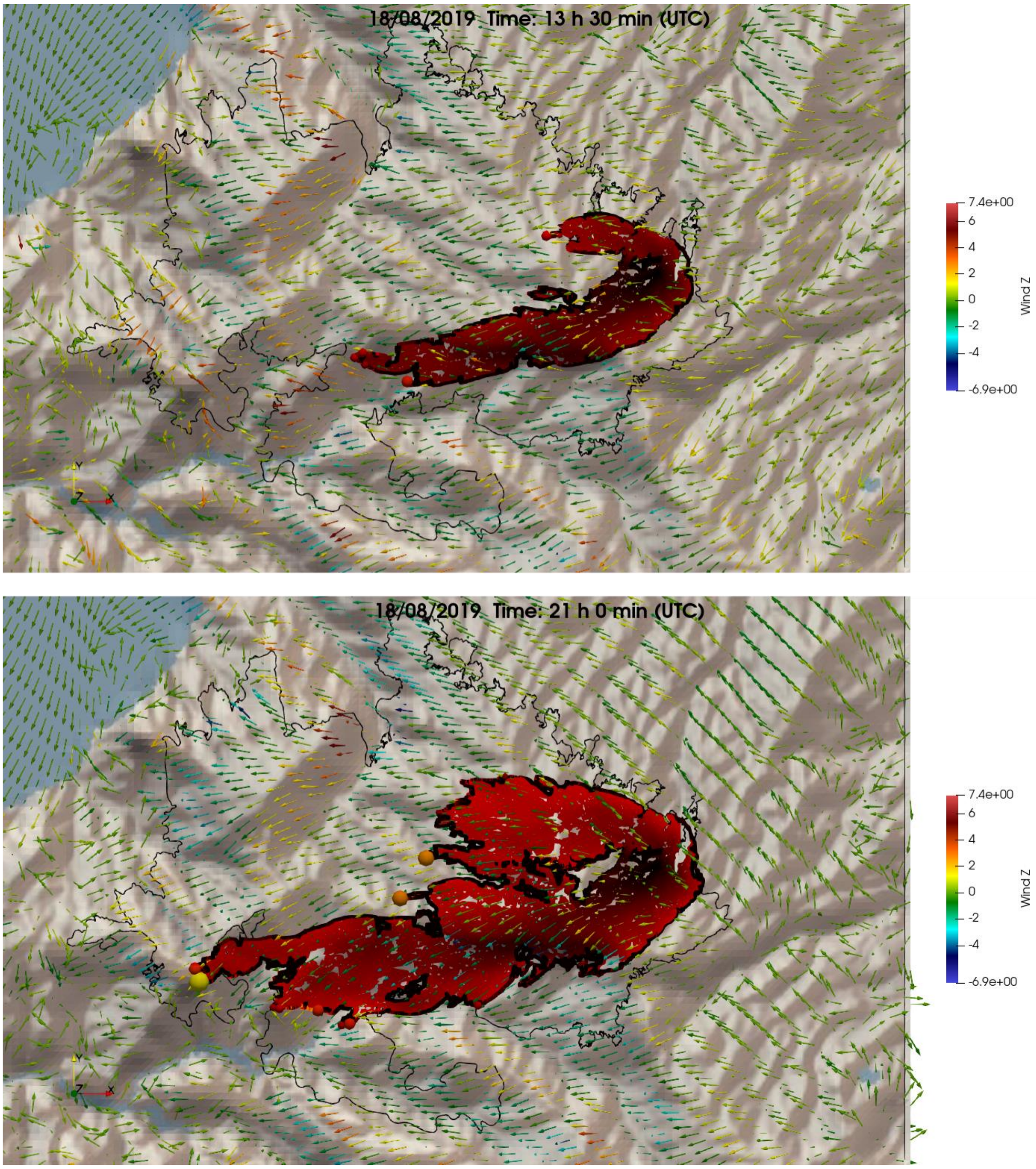


Figure 28: Surface wind field (coloured arrows) along with the propagating fire fronts (illustrated with dots whose size is proportional to the propagation speed. The simulated burned area within the fronts is color coded by time of burning. The illustrated snapshot refers to 2019-08-17 13:30:00 UTC and 2019-08-18 21:00:00 UTC. The thin black contour shows the total burned observed area for comparison.

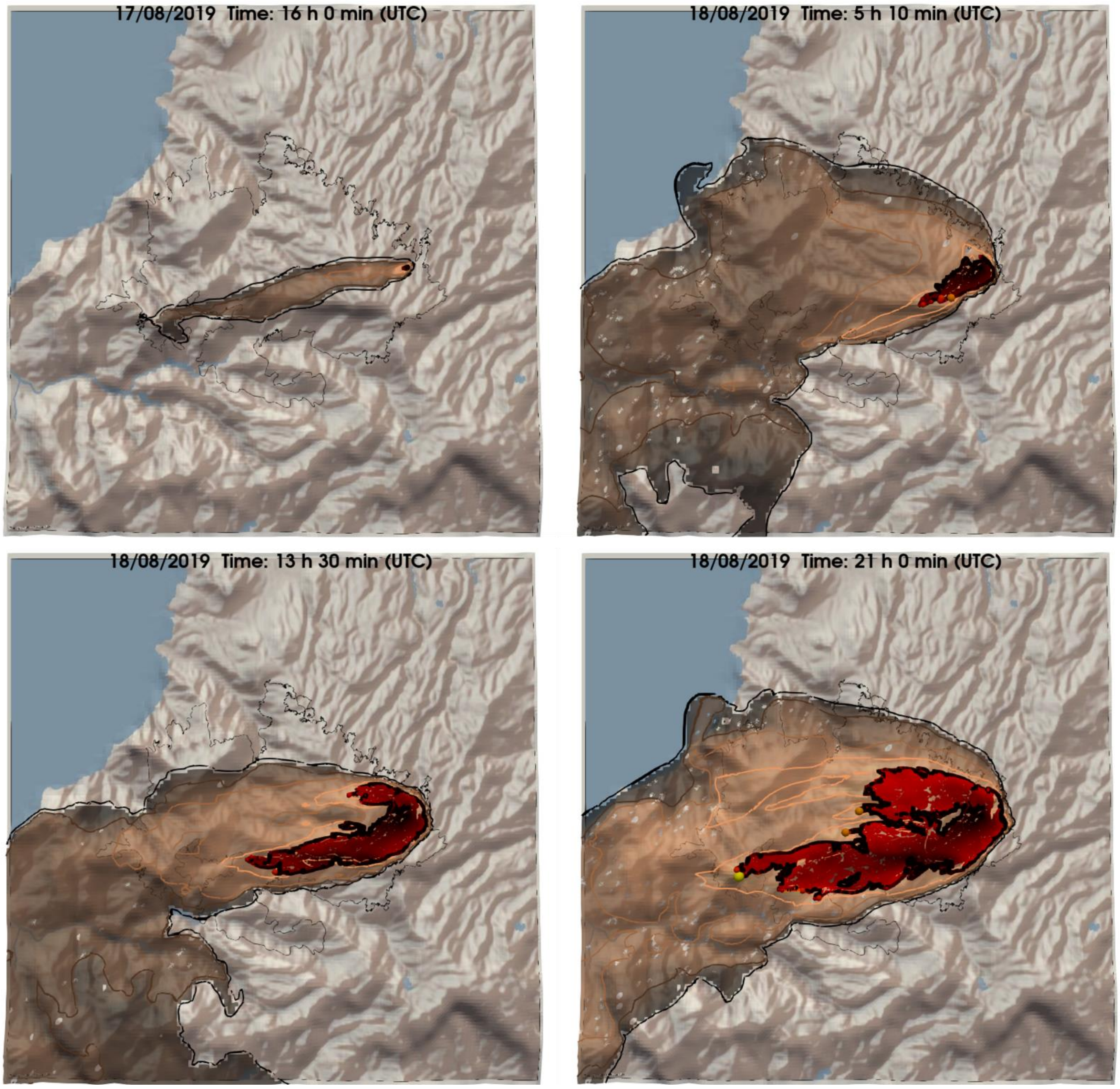


Figure 29: Surface smoke concentration (orange to brown concentration) along with the propagating fire fronts (illustrated with dots whose size is proportional to the propagation speed. The simulated burned area within the fronts is colour coded by time of burning. The illustrated snapshot refers to 2019-08-17 13:30:00 UTC and 2019-08-18 21:00:00 UTC. The thin black contour shows the total burned observed area for comparison.

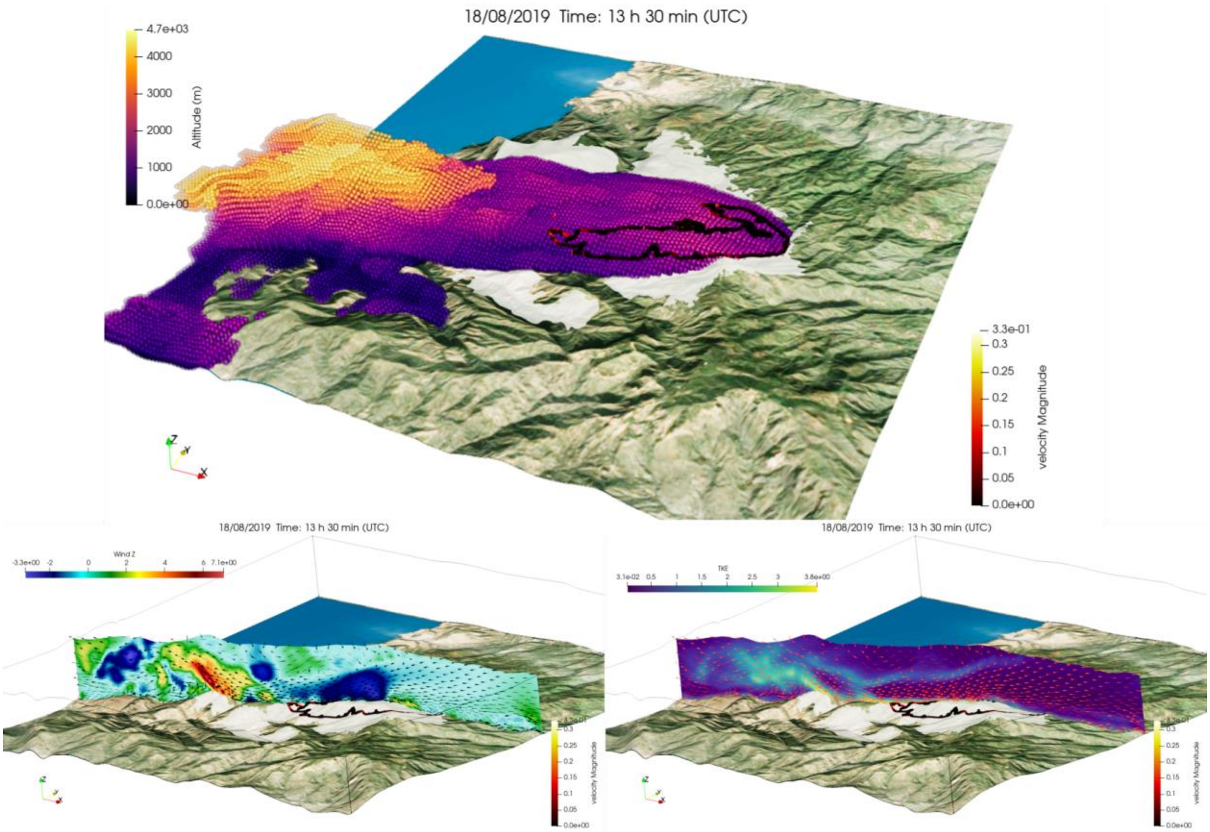


Figure 30: 3D view of the smoke plume at 2019-08-17 13:30:00 UTC, the color coding is proportional to the plume altitude. In the lower part of the figure two sections along the plume axis show the vertical wind field (left) and the turbulent kinetic energy (right). The fire fronts are also highlighted.

Finally, in Figure 31 showing the evolution of the smoke plume at the large scale (External domain) The plume develops to the west and shifts gradually to the south in the later hours of the simulation, A comparison with the pictures taken from the satellite Aqua MODIS in date 2019-08-18 is also illustrated for the sake of comparison.

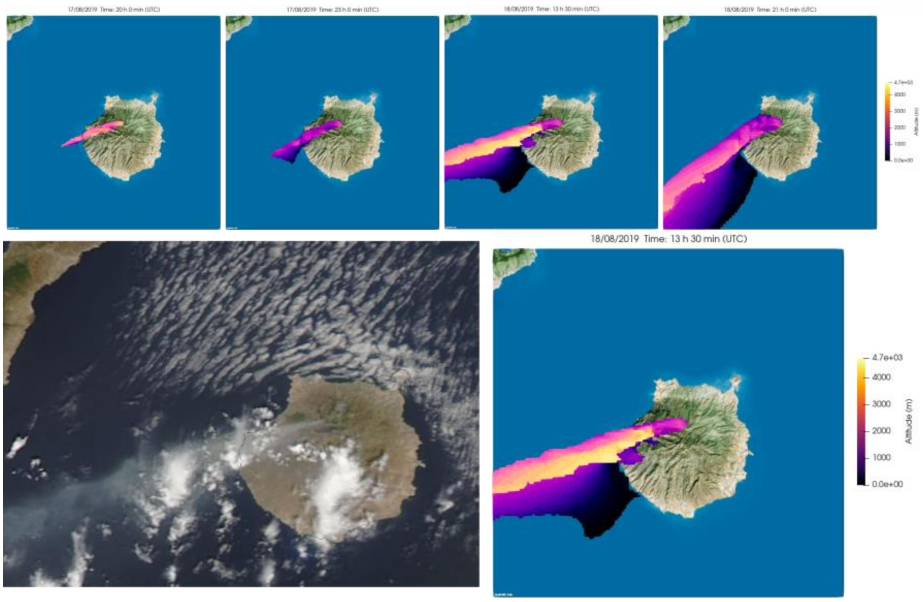


Figure 31: Large scale evolution of the smoke plume (color code proportional to smoke altitude).

4.5. Final Graphical Representations

Identifying Key Information Needs of Operational Personnel

The results generated by the coupled ForeFire/MesoNH model are substantial in size, making them challenging to manipulate and visualise. Each output corresponds to a nested domain at a specific simulation time and is saved as a NetCDF (Network Common Data Form) file, a format commonly used in meteorology for storing large, multi-dimensional datasets. Following the configuration of the MesoNH numerical weather prediction code, all primary meteorological variables (such as wind components, pressure, temperature, humidity, water species density, and turbulent energy) are stored across the full three-dimensional grid. To streamline data sharing for implementation on the ISS, we initiated discussions with the involved Living Labs to identify the most critical data.

The final selection was guided by three main concerns expressed by firefighters regarding the predictive insights needed in a hypothetical firefighting scenario. Their first concern is identifying **sections of the fire front that may be susceptible to rapid, unpredictable shifts in behaviour**. Second, they are focused **on areas where reduced visibility could increase risk.** Finally, they need **predictive insights into both the broad and localised structures of the wildfire plume to assess potential pyroconvection.** The meteorological variables which were chosen to address such concerns were summarised in three types of plots which are illustrated below. These were presented, discussed and improved following the feedback and exchanges with the LLs:

- **Plot 1: Surface Wind Fields and Turbulence**: Information on wind patterns and turbulence near the surface, which directly affect fire behaviour and firefighter safety. These results are shown along with the simulated fire front and its instantaneous velocity.

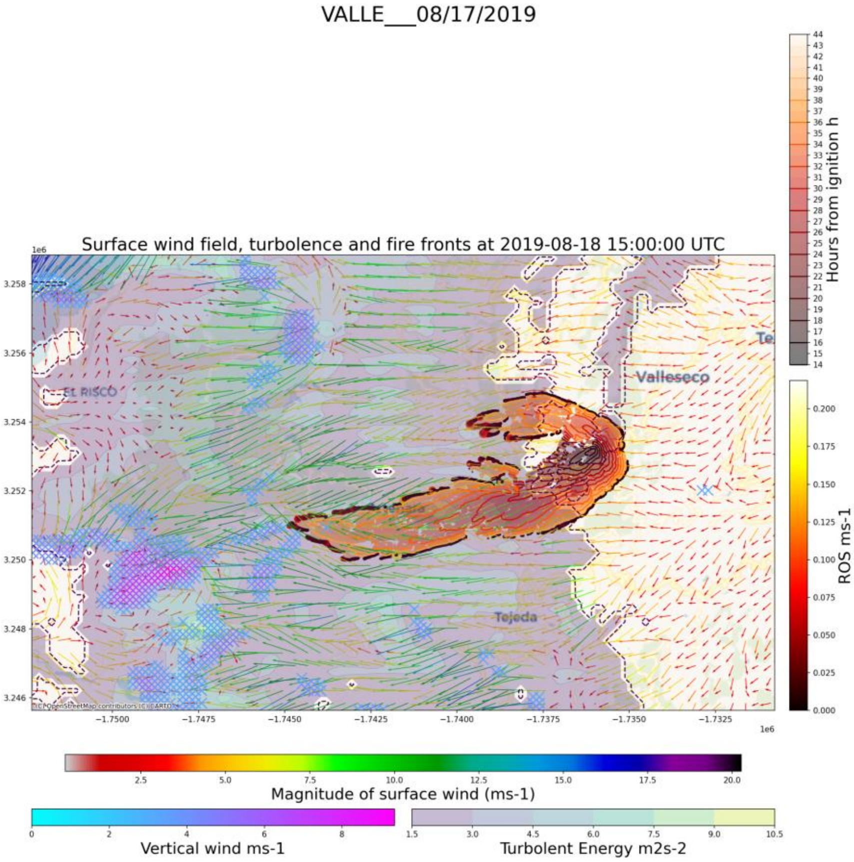


Figure 32: type 1 plot: Surface wind field is displayed with coloured arrows whose colour code and dimension proportional to the speed module). Regions characterised by relatively strong wind gusts (Turbulent Kinetic Energy, TKE, above 1.5 m2s-2) are displayed by filled violet contours. Strong upward airflows (above 3 ms-1) are indicated with crosses using a colour scale from light blue to purple. Moreover, we illustrate the fire front using points which are proportional to the Rate of Spread (ROS, ms-1). Internal contours show the arrival time of the fire with a frequency of two hours from ignition up to the current time (measured in hours from midnight of ignition day).

- **Plot 2: Smoke Production and Dispersion**: Data on smoke concentration at the ground level and its dispersion, important for air quality assessments and visibility concerns. These results are shown along with the simulated fire front and its instantaneous velocity.

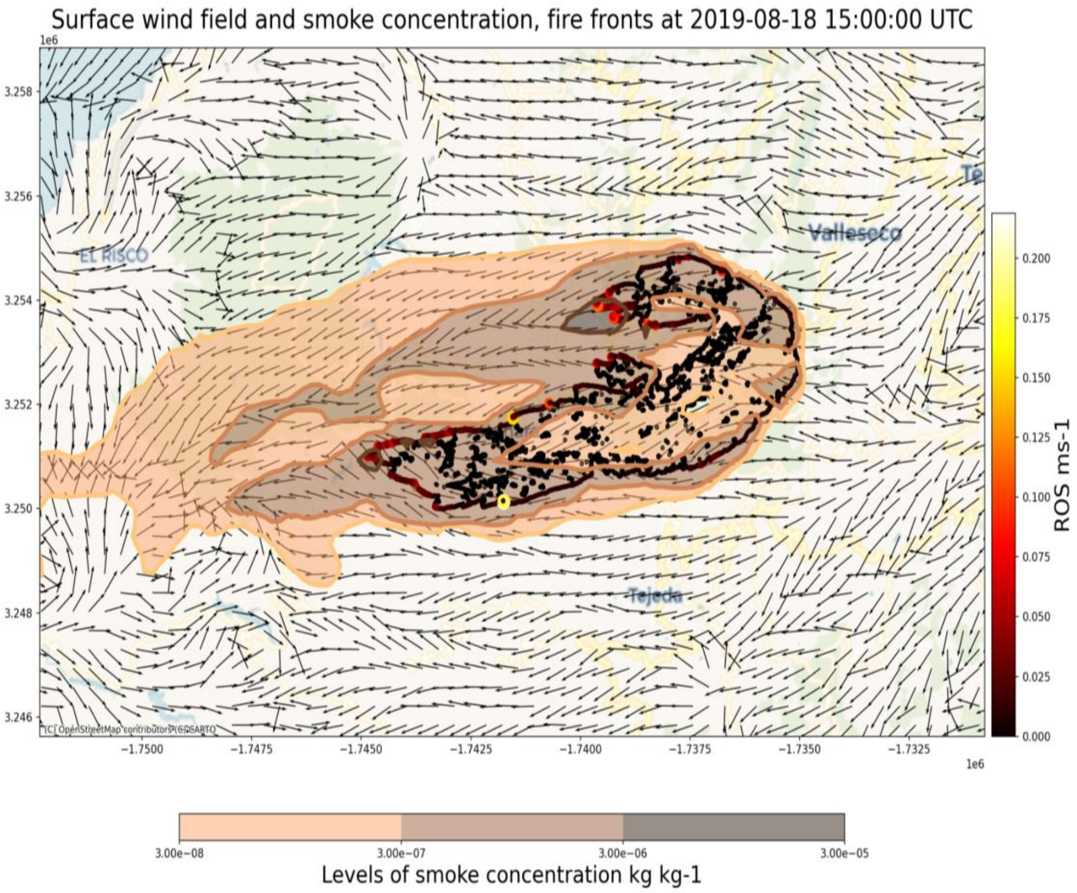


Figure 33: Type 2 plot: Smoke concentration at the ground (kg/kg-1) is illustrated using orange contours. The direction of the surface wind field is illustrated with black arrows. The fire front is illustrated using point sizes proportional to the ROS (ms-1).

- **Plot 3: Potential for Convective Cloud Formation**: Insights into the development of convective plumes and the possibility of the fire generating its own weather, which can lead to unpredictable fire behaviour.

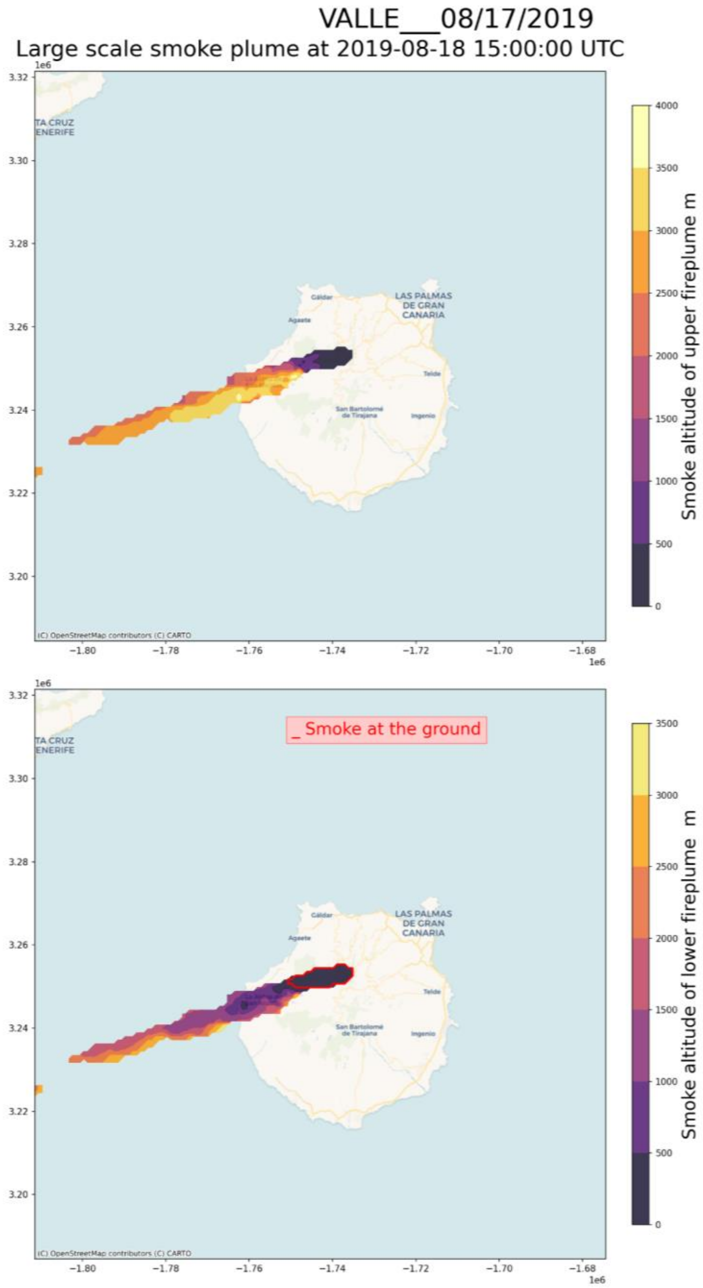


Figure 34: Type 3 plot: Smoke altitude at large length scale. Top figure illustrate the altitude of upper surface of the smoke cloud, while the bottom figure displays the altitude of the lower surface of the plume, with evidence of the smoke at the ground, which is highlighted in red.

We remark that despite the fact that the graphs and displayed data were appreciated and understood by the members of the consulted LLs, since the tool has not yet been tested in a real Extreme Wildfire Event (EWE) scenario, we are currently limited in our ability to draw definitive conclusions about its practical utility for supporting fire attack tactics in the field. Conducting real-time testing during an actual EWE, in direct collaboration with at least one of the LLs, would be essential to fully assess its effectiveness. Such collaboration would enable us to make more conclusive statements about the approach's value in operational settings.

All the post-processing procedures allowed to pass from the initial MesoNH output to the illustrated plots, including data compilation and plotting scts, are available as python script in the Forefire github repository.

4.6. Integration with ISS Platform

The main task was to develop Python scripts, primarily using the Malu Lib library, to generate NetCDF files containing the key outputs of the fire propagation and atmospheric simulation models. The generation process relies on xarray data libraries, which efficiently handle large datasets. From the complete model outputs, only selected fields of interest are used to create the necessary visual representations. These data are then compiled into a NetCDF file, incorporating a specific geographic projection system and a set of metadata to ensure compatibility with Tecnosylva's platform.

Integrating with Tecnosylva's platform required adjustments to align the file format and metadata with the platform's technical specifications. A critical aspect was adhering to specific data structuring conventions and variable naming, allowing seamless integration without additional modifications. Additionally, the projection system needed to be adapted to meet the end-users' requirements, thus enhancing the operational value of the simulation outputs.

Once these parameters were agreed upon with Tecnosylva, a file transfer protocol was established. A shared storage platform, such as a Drive system, was chosen where NetCDF files could be uploaded for each fire simulation event. This process ensures traceability and accessibility, allowing Tecnosylva's teams to directly integrate the files into their platform for visualisation and analysis. Regular iterations have been conducted to refine the data outputs based on feedback, improving their utility and precision for decision-making purposes. More details about the ISS in D 5.2.

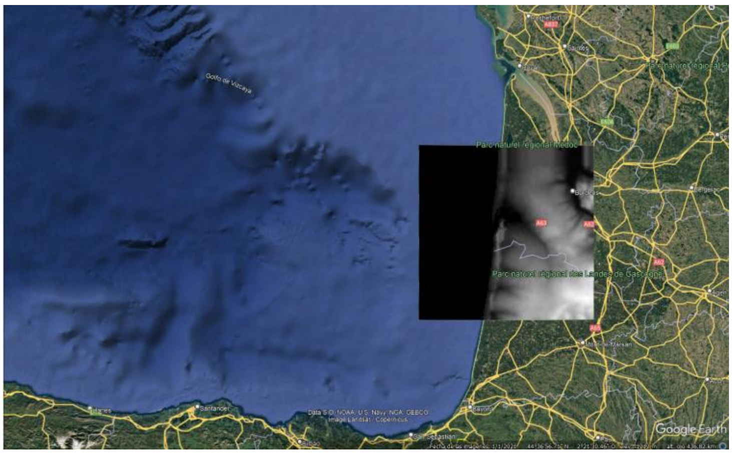


Figure 35: Coupled model fire data in the ISS.

5. VR visualisation for communication and experiments in operations

Innovation in VR and AR visualisation of the coupled simulations has been developed to experiment in operational testing and public awareness efforts. These developments are just preliminary tests, to demonstrate what could be such visualisation. We did not aim to build an operational system out of it but took the opportunity of Fire-Res to interact with operational users and gather their first impressions on the use of AR/VR in decision making. Comments were encouraging, suggesting that working on new interface may be of interest in a more structured project.

Initially, we focused on creating awareness videos that resemble scientific videos to visually communicate complex phenomena like pyroconvection. One notable example is the fire in Pedrógão Grande, Portugal, where we used a unique rendering technique with 3D software in a rectangular cube format. This allowed us to produce 360-degree videos that, when uploaded to platforms like YouTube, could be viewed immersively with simple, low-cost headsets such as Google Cardboard. These videos provide a fixed-point, immersive experience accessible to anyone with a smartphone, offering the public a tangible way to grasp the dynamics of such events.

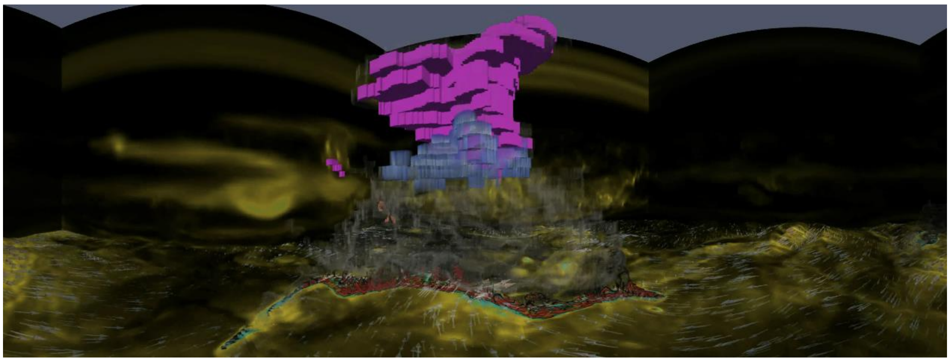


Figure 36: A 360 video in equirectangular projection, to view it in immersive context: https://www.youtube.com/watch?v=tObUvHXSTRk&t=6s

The next step was to explore an interactive VR experience where users could navigate a virtual territory using advanced VR headsets, such as the MetaQuest 3. By integrating Airframe and the Tri.js library, we enabled real-time interactivity in a 3D environment. Within this setup, users can engage with fire simulations interactively: not only can they observe ongoing simulations but also trigger new ones in real time. The experience goes beyond static visuals by allowing users to visualize atmospheric elements like air currents and surface winds and experiment with smoke transport by “injecting” smoke in various locations, enabling a backward analysis of its origin. This interaction makes the experience more realistic and educational, providing insights into fire dynamics and atmospheric interactions.

This VR environment is fully online and accessible through a browser within the VR headset, without needing software installation. Users can simply navigate to a dedicated project page, like the FireHeads platform, to begin exploring the interactive features. This seamless access democratizes advanced visualization tools, offering both operational users and the general public a compelling and informative way to engage with fire simulations and environmental phenomena.

This tool is accessible at the following link: https://forefire.univ-corse.fr/fire-res/.

Figure 37: Mark Finney, Member of the Fire-Res advisory board testing the immersive experiments during the General Assembly in Bordeaux.

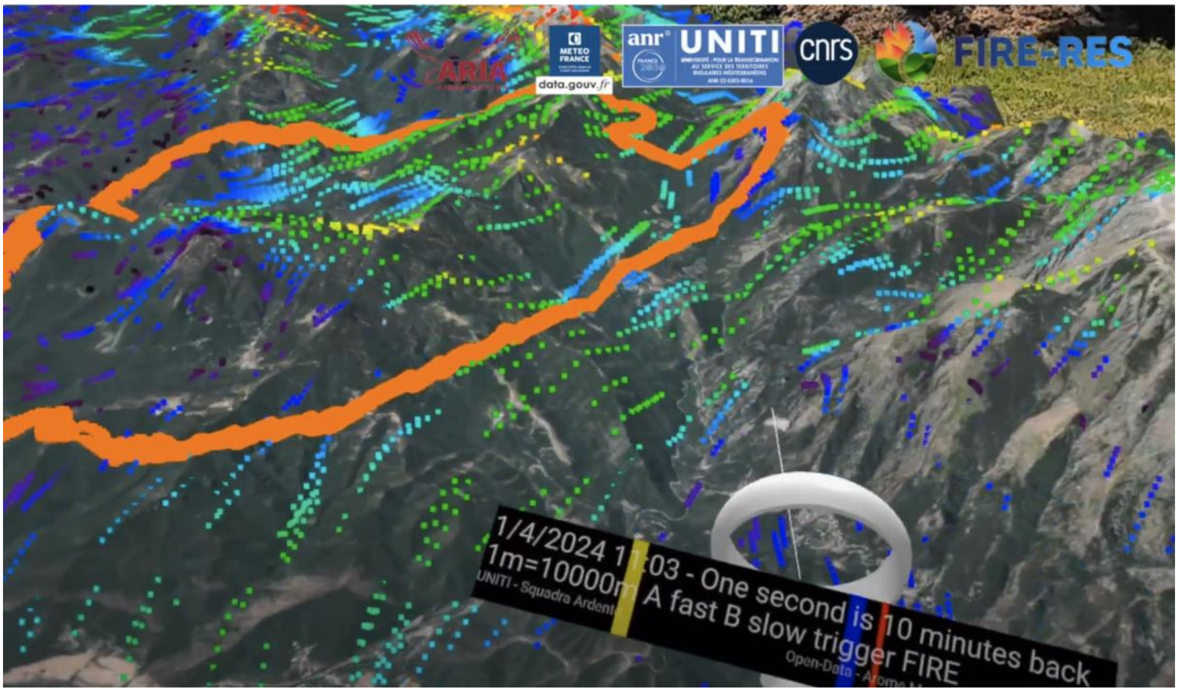


Figure 38: Figure 37: The view inside the headset.

6. Conclusions

Through this project, we have progressed from a Technology Readiness Level (TRL) of 5 to 7. Initially, we had a prototype capable of producing coupled atmosphere-fire simulations. We have now developed a system that can be deployed operationally to forecast fire-atmosphere interactions. This system generates a 24-hour forecast within an initial computation time of two hours and updates automatically every 12 hours, allowing for continuous simulation of fire progression in 10-minute intervals over a 24-hour period.

Despite these advancements, providing this service beyond the scope of the FIRE-RES program requires further development. Establishing an associated computing centre is necessary to run simulations as needed, ensuring that computational resources are available during critical periods. Additionally, incorporating higher-quality fuel map data at a finer resolution of at least 10 metres is essential. While such data are being developed by other work packages within the program, they require refinement to meet our resolution requirements.

We have demonstrated the feasibility of integrating these simulations with a transnational European platform, enabling the delivery of actionable forecasts to decision-makers in the field. To enhance the system further, we consider the integration of artificial intelligence (AI) technologies. By leveraging new observation systems, AI can process extensive data on extreme fires from recent years, improving model optimization and forecast accuracy. Gathering and formatting data on these fires is a strong requirement in this respect and of paramount importance to run these studies.

Future developments may include real-time updates during fire events, incorporating data assimilation techniques that go beyond traditional fire perimeter information. This involves integrating diverse, parcel-level data from the field through a generic platform, particularly when satellite observations are unavailable. Such real-time data assimilation can refine forecasts and support decision-making processes during active fire incidents.

By continuing to develop these capabilities, we aim to improve the effectiveness of wildfire management strategies across Europe. Enhancing our system with AI and real-time data assimilation holds the potential to provide more accurate and timely information, contributing to better preparedness and response efforts. This progress supports the resilience of landscapes and communities faced with the increasing threat of extreme wildfires.

7. Bibliographic references

Mandel, J., Beezley, J.D., and Kochanski, A.K., 2011. Coupled atmosphere-wildland fire modeling with WRF-Fire version 3.3. *Geoscientific Model Development Discussions*, 4(1), pp.497-545.

Mandel, J., Amram, S., Beezley, J.D., Kelman, G., Kochanski, A.K., Kondratenko, V.Y., Lynn, B.H., Regev, B., and Vejmelka, M., 2014. Recent advances and applications of WRF–SFIRE. *Natural Hazards and Earth System Sciences*, 14(10), pp.2829-2845.

Giannaros, T.M., Kotroni, V., and Lagouvardos, K., 2019. IRIS–Rapid response fire spread forecasting system: Development, calibration and evaluation. *Agricultural and Forest Meteorology*, 279, p.107745.

Toivanen, J., Engel, C.B., Reeder, M.J., Lane, T.P., Davies, L., Webster, S., and Wales, S., 2019. Coupled atmosphere-fire simulations of the Black Saturday Kilmore East wildfires with the unified model. *Journal of Advances in Modeling Earth Systems*, 11(1), pp.210-230.

Peace, M., Greenslade, J., Ye, H., and Kepert, J.D., 2022. Simulations of the Waroona fire using the coupled atmosphere–fire model ACCESS-Fire. *Journal of Southern Hemisphere Earth Systems Science*, 72(2), pp.126-138.

Lac, C., Chaboureau, J.P., Masson, V., Pinty, J.P., Tulet, P., Escobar, J., Leriche, M., Barthe, C., Aouizerats, B., Augros, C., and Aumond, P., 2018. Overview of the Meso-NH model version 5.4 and its applications. *Geoscientific Model Development*, 11(5), pp.1929-1969.

Campos, C., Couto, F.T., Filippi, J.B., Baggio, R., and Salgado, R., 2023. Modelling pyro-convection phenomenon during a mega-fire event in Portugal. *Atmospheric Research*, 290, p.106776.

Couto, F.T., Filippi, J.B., Baggio, R., Campos, C., and Salgado, R., 2024. Numerical investigation of the Pedrógão Grande pyrocumulonimbus using a fire to atmosphere coupled model. *Atmospheric Research*, 299, p.107223.

Couto, F.T., Filippi, J.B., Baggio, R., Campos, C., and Salgado, R., 2024. Triggering Pyro-Convection in a High-Resolution Coupled Fire–Atmosphere Simulation. *Fire*, 7(3), p.92.

Baggio, R., Filippi, J.B., Truchot, B., and Couto, F.T., 2022. Local to continental scale coupled fire-atmosphere simulation of large industrial fire plume. *Fire Safety Journal*, 134, p.103699.

Clements, C.B., Kochanski, A.K., Seto, D., Davis, B., Camacho, C., Lareau, N.P., Contezac, J., Restaino, J., Heilman, W.E., Krueger, S.K., and Butler, B., 2019. The FireFlux II experiment: a model-guided field experiment to improve understanding of fire–atmosphere interactions and fire spread. *International Journal of Wildland Fire*, 28(4), pp.308-326.

Filippi, J.B., Bosseur, F., Mari, C., and Lac, C., 2018. Simulation of a large wildfire in a coupled fire-atmosphere model. *Atmosphere*, 9(6), p.218.

Firecaster ANR research program - ANR-16-CE04-0006 - https://www.firecaster.org

Filippi, J.B., Bosseur, F., Mari, C., Lac, C., Le Moigne, P., Cuenot, B., Veynante, D., Cariolle, D., and Balbi, J.H., 2009. Coupled atmosphere-wildland fire modelling. *Journal of Advances in Modeling Earth Systems*, 1(4).

Benali, A., Guiomar, N., Gonçalves, H., Mota, B., Silva, F., Fernandes, P.M., Mota, C., Penha, A., Santos, J., Pereira, J.M. and Sá, A.C., 2023. The portuguese large wildfire spread database (PT-FireSprd). Earth System Science Data Discussions, 2023, pp.1-50.

Cardil, A., Monedero, S., Schag, G., de-Miguel, S., Tapia, M., Stoof, C.R., Silva, C.A., Mohan, M., Cardil, A. and Ramirez, J., 2021. Fire behavior modeling for operational decision-making. Current Opinion in Environmental Science & Health, 23, p.100291.

Cardil, A., Monedero, S., SeLegue, P., Navarrete, M.Á., de-Miguel, S., Purdy, S., Marshall, G., Chavez, T., Allison, K., Quilez, R. and Ortega, M., 2023. Performance of operational fire spread models in California. International journal of wildland fire, 32(11), pp.1492-1502.

8. Annex

IA 5.2 from the initial Document

In the signed final document (end of 2021) the description of this AI was redacted as:

IA 5.2. Demonstration of real-time EWE simulation and smoke spread based on coupled fire-atmosphere approaches using of HR weather data (TSYLVA) [WP5] [LL: All]

[FMC phases: A, B, C] Development and testing of a coupled fire-atmosphere spread model to consider the effect of pyro convection in fire behaviour, progression, and impact estimations. It will include the validation of EWE erratic propagation due to pyro convection or extreme winds through large scale coupled fire/weather simulation re-analyses on several extreme large fires in Europe since 2010. Plume and smoke in-drafts will also be qualified through numerical tools (Wildfire Analyst and ForeFire). ECMWF as well as enhanced high-resolution weather models will be used. Finally, Virtual Reality videos will be produced for public awareness and communication purposes.

Deviations from this Document: All the goals of the IA have been addressed, going from a TRL 5 to TRL 7 with demonstration of the system in an operational environment. This document is marked as deliverables 5.3 (Table 3.1.c): *D5.3. IA 5.2 brief: Modelling the EWE and smoke spread based on coupled fire-atmosphere approaches (M36, **CNRS**, DEM, PU)*

One other deviation is the action end date (M36) that moved to a final (M42) (change accepted in general assembly and the project officer) because of initial delays in recruiting at CNRS.

This IA 5.2 is linked to task 5.3 that itself is action IA 5.1 presented in deliverable 5.2, (note, the volatile fuel compound (sensors) is IA 5.6 by CSIC and while integrated in the ISS is not used or was planned to be used in simulations):

Task 5.3. Modelling and decision support system tools (D&MS: D5.3; D5.4; D5.5; D5.7; D5.10; MS5.3; MS5.4). [M12-36] *(TSYLVA, CFRS, CNRS, CSIC, MITIGA, VTT, NIBIO(SFRS))*

This task implements modelling and DSS in the "umbrella" system developed in Task 5.1. These shall support decision makers in operations, preparedness and planning through the integration of data gathered in task 5.2. Modelling systems will include forest fire and smoke behaviour models. ***It shall address the improvement of fire and air pollutant dispersion modelling systems to better estimate the EWE progression through analysis of atmospheric conditions and volatile fuel components conducting to convective fires (linked to IA 5.2)****. These models and DSS will contribute to controlling any extreme wildfire in less than 24h, reduce emissions and building losses. These tools shall increase data transferability between WPs using standard formats for documenting models and their analyses to be more comprehensive for end-users. The aim is to facilitate the use of high-end, accurate and advanced technologies at the forefront of real-world planning and operational environments with direct impact on response and preparedness to EWEs.*

FIRE-RES