D1.4. IA 1.2 brief: Testing key inputs for atmospheric data analysis using new knowledge and expertise on EWE

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Abstract: Extreme Wildfire Events (EWE) cause great impact, damage and fatal consequences around the world. The mechanisms and processes involved in EWE are still unclear, and difficult to predict, although it seems that the coupling between fire and atmosphere is a crucial point. So, data about EWE needs to be collected and analysed properly to increase knowledge about the phenomena. This data is necessary to understand EWE behaviour and the processes involved. Gathering information on EWE behaviour and associated driving factors is important to predict when and where these events will occur and to make the necessary decisions to minimise the negative consequences they currently entail.

Many of the challenges identified in FIRE-RES D1.1 require a better understanding of the EWE phenomenon, and this is not possible if the key elements are not monitored. Although the need for data seems overwhelming, we should not be paralysed because urgent decisions have to be made every fire season.

This deliverable identifies the key parameters to understand how EWE works (Table 1). It also proposes an adaptation of existing wildfire analysis methodology to integrate these parameters and facilitate decision making (Section 6). Also, in Section 4 it is proposed different tools and methods to obtain some of these key parameters through the monitoring of EWEs within the FIRE-RES project.

Key words: EWE; extreme wildfire event; key parameters; RADAR; radiosondes.

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List of acronyms

ABL: Atmospheric Boundary Layer

AFAN: Advanced Fire Analysis Network

ANEPC: Autoridade Nacional de Emergência e Proteção Civil (Portugal)

CAPE: Convective Available Potential Energy

CCL: Convective condensation level

CET: Central Europe Time

CFRS: Catalan Fire and Rescue Service

CIN: Convective Inhibition

CNRS: Centre National de la Recherche Scientifique

CONAF: Corporación Nacional Forestal (Chile)

CTFC: Forest Science and Technology Centre of Catalonia

D: deliverable

DCAPE: Downdraft convective available energy

DLS: Deep Layer Shear

EL: Equilibrium Level

EWE: Extreme Wildfire Events (In accordance with the definition in D1.1 of FIRE-RES project by Castellnou et al., 2022)

EWED: Extreme Wildfire Events Data Hub for Improved Decision Making

FIRE-RES: Fire Resilient territories in Europe

FIRE-RES: Innovative Technologies and Socio-Ecological-Economic Solutions for FIRE-Resilient Territories in Europe

FLI: Fireline intensity

FWI: Fire Weather Index

GA: Grant Agreement

GAUF: Grupo de Análise e Uso do Fogo (GAUF), da Força Especial de Proteção Civil (FEPC) da ANEPC (Portugal)

HF: Heat Fluxes

IA: Innovative Action

LCL: Lifting Condensation Level

LIDAR: Light Detection and Ranging

LLS: Low Level Shear

NCL: Free Convection Level

NERO: European Network on Extreme fire behaviour

NIPV: Netherlands Institute for Public Safety

NOA: National Observatory of Athens (Greece)

PyroCb: Pyrocumulonimbus

PyroCu: Pyrocumulus

RADAR: Radio Detection and Ranging.

ROS: rate of spread

TCON: Convective temperature / Triggering temperature / Release temperature.

TRL: Technology Readiness Levels

VTT: VTT Technical Research Centre of Finland Ltd

WP: work package

WS: workshop

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1. Introduction

Innovative Action 1.2 (IA 1.2) involves *Testing key inputs for atmospheric data analysis using new knowledge and expertise on Extreme Wildfire Events*. Its objective is to develop a novel methodology for fire analysis, encompassing new atmospheric parameters, drivers, tipping points, and triggers that promote the growth of EWEs and the PyroCb process. This proposed methodology was intended to be tested during the project for any emerging Extreme Wildfire Events (EWEs), using available tools at any given time to identify key parameters.

While the proposed methodology specifies the necessary parameters and associated data for implementation, it does not develop new collecting tools whenever those do not exist. Consequently, the testing of the key parameters will be conditional on the availability of these tools and of wildfire analysis teams throughout the project and at implementation locations.

The emphasis of this methodology lies in the Extreme Wildfire Events, as defined in the D1.1. Transfer of lessons learned on extreme wildfire events to key stakeholders (D1.1_FIRE-RES_Transfer_of_LL_on_EWE.pdf) is outlined as follows:

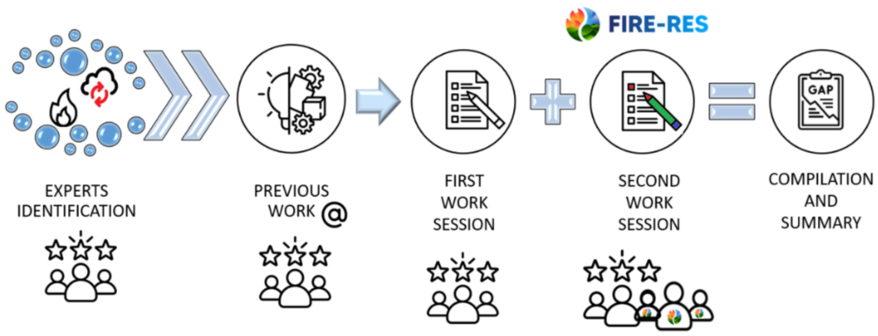
Extreme Wildfire Events (EWE) are defined as wildfires with large-scale complex interactions between fire and atmosphere generating pyroconvective behaviour, coupling processes, that results in fast, intense, uncertain, and fast-paced changing fire behaviour.

- It results in fire behaviour exceeding the technical limits of control (fireline intensity 10.000 kW/m; rate of spread >50 m/min; spotting distance > 1 km and exhibiting prolific to massive spotting based on Tedim et al.2018 [Fig.14], and extreme growth of rate (surface per hour, ha/h) values).
- At the same time, this extreme fire behaviour is unpredictable using current operative models, with moments of observed fire behaviour highly exceeding the expected one. This overwhelms the decision-making capacity from the emergency system (firefighter crews and emergency managers, infrastructure managers and civilian population).

It may represent a heightened threat to crews, population, assets, and natural values, and may cause relevant negative socio-economic and environmental impacts.

2. Process used to develop D1.4

The following steps have been taken to carry out the Innovative Action 1.2:



STEP 1. Experts' identification

The initial phase of this methodology commenced by engaging with professionals involved in EWE monitoring, from teams accustomed to handling data pertaining to such scenarios. The list of experts is detailed in the table presented in this section.

The selection of operational experts (E. Marques, ANEPC[1]; F.Silva, GAUF-ANEPC[1], J. Saavedra, CONAF[1]; M. Castellnou, CFRS[1]) was based in their involvement in real EWE who have accumulated experience in EWEs such as Pedrógão Grande 2017, Santa Coloma de Queralt 2021, Santa Anna – Biobio Region 2023.

The inclusion of Mitiga Solutions SL member (T. Artés) was included on his expertise in projects associated with modelling, data assimilation, calibration methods, GIS, remote sensing, parallel data processing and data mining related to wildfires.

NIPV[1] member (B. Verhoeven) was selected as an expert meteorologist, who carried field work with CFRS and NIPV during the 2020-2021 forest fire campaigns and as a partner from the European countries where wildfires have not been considered traditionally as a threat.

NOA[1] member (Theodor M. Giannaros) was proposed for his expertise on atmospheric modelling, and wildfire monitoring, carried out mainly in collaboration with GAUF (ANEPC). A second NOA member was also included (G. Papavasileiou as expert on atmospheric Sciences, numerical weather prediction (NWP) modelling, remote sensing and programming.

STEP 2. Preparatory phase

In the preliminary stages, the experts were consulted regarding the types of data typically required for EWE monitoring. The aim was to decode what types of data would be beneficial to identify, monitoring, and comprehend EWE behaviour to have the capacity to formulate of decision-making during EWE emergency management.

STEP 3. First working session

The first working session was conducted online on 17 January 2023 from 09:00-11:30h CET. In this meeting, experts were queried about the current datasets utilized for wildfire monitoring, and the potential future data beneficial for monitoring the fire-atmosphere interaction of EWE. The subsequent, this is, information that are particular to EWE and that should be monitored to enhance comprehension of their behaviour and forecast their development, are the main focus of this deliverable.

[1] See list of acronyms at the beginning of the document.

At the first meeting, two approaches were recognized. On one side, parameters that are currently utilized (refer to Table 2), conversely, key parameters that would be essential to monitor in order to understand and anticipate EWE (refer Table 1).

Image 1. First working session

STEP 4. Second working session

The subsequent working session was conducted virtually on 14 April 2023 from 09:00-11:00h CET and included project collaborators. Based on the key parameters for monitoring EWE that were identified in the primary session (Table 1, Table 2), throughout the subsequent work session an effort was made to determine whether a project partner is responsible for acquiring any specified key parameter or is engaged in an IA (Innovation Action) that can provide it. Possessing these factors is the foundation for being capable of monitoring EWE behaviour and to anticipate the phenomena.

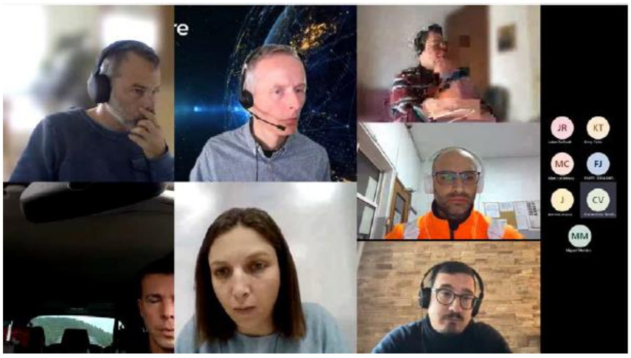


Image 2. Second working session

STEP 5. Compilation and summary

As the concluding phase of the critical factor identification process, the perspectives and outcomes of the experts gathered during the working sessions were compiled.

On one side, the different conclusion based on the experiences and views of the experts were drawn. On the other hand, Section 4 encompasses the methodology for monitoring EWE, which was formulated subsequently considering the outcomes from the work sessions, but it was not deliberated during the work sessions. The procedure is grounded on the evaluation process that is already conducted in response organisations taking into consideration the crucial parameters recognized.

1st working session (invited experts)	2nd working session (invited experts & FIRE-RES project partners)
Brian Verhoeven, NIPV; Eduardo Marqués, GAUF-ANEPC; Fábio Silva, GAUF-ANEPC; Georgios Papavasileiou, NOA; Jorge Saavedra, CONAF; Marc Castellnou, CFRS; Theodore M. Giannaros, NOA; Tomàs Artés, MITIGA Solutions SL.	Aymen Moghli, CTFC; Constantino Varotsos, NOA; Edgar Nebot, CFRS; Eduardo Marqués, ANEPC; Georgios Papavasileiou, NOA; Gerald van der Grijn, SPIRE; Jean-Baptiste Filippi, SPE - UMR 6134 CNRS Université de Corse; Jean-Luc Dupuy, INRAE; Julien Ruffault, INRAE; Marc Castellnou, CFRS; Miguel Mendes, TECNOSYLVA; Pau Brunet, CTFC; Terhi Kling, VTT; Theodore M. Giannaros, NOA; Tomàs Artés, MITIGA Solutions SL.

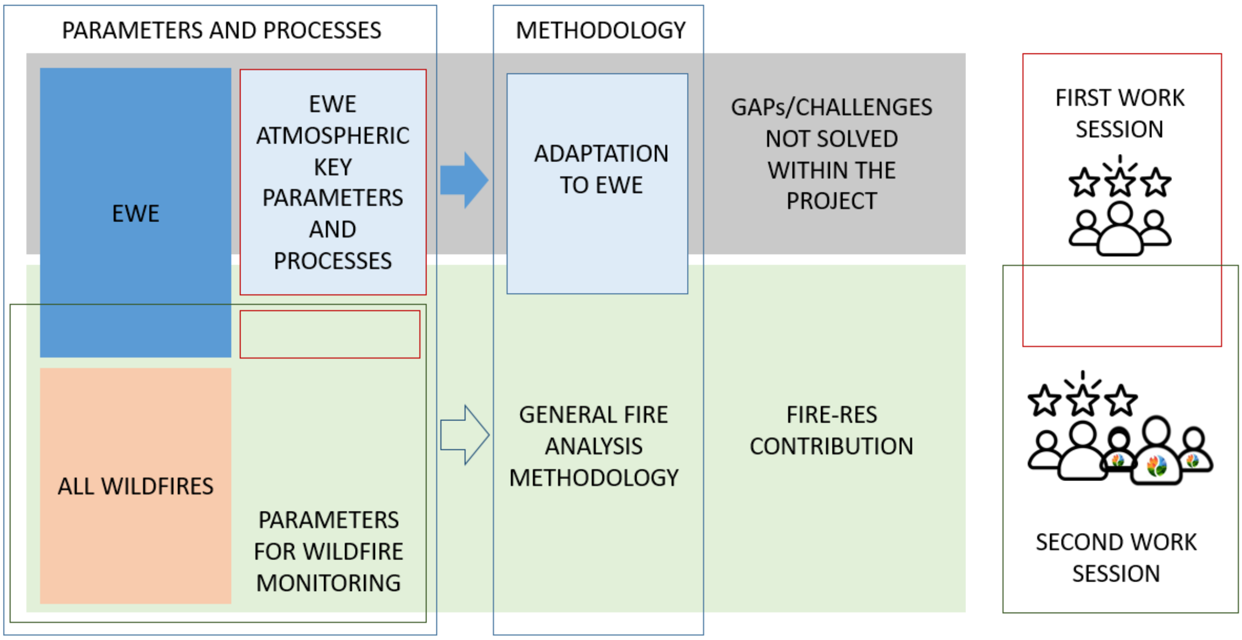


Figure 1. Scheme of the conceptual approach for deliverable 1.4.

3. EWE key parameters and processes

Extreme Wildfire Events (EWE), as delineated in the definition provided in section 1, exhibit specific behaviour and characteristics that set them apart from other types of fire. Hence, it is imperative to identify the factors linked to EWE incidence and behaviour of such occurrences, in order to enhance monitoring and prediction beyond current capabilities.

This section elucidates the array of parameters pinpointed by the experts, during collaborative sessions, as pivotal elements in comprehending, foreseeing, and overseeing EWE, as expounded upon in section *2. Process used to develop D1.*.

Consequently, the consolidation of parameters and procedures enumerated in Table 1 serves the purpose of this deliverable. Certain parameters outlined in the table are presently unquantifiable due to technical difficulties or the lack of the necessary tools, thus table aims to stimulate innovation.

List of key specific parameters for monitoring EWE

Table 1 shows the list of key specific parameters for monitoring EWE and a definition for each of them is included in Annex 4. These definitions are not derived from any consensus or specific reference. They are included only to clarify the explanation of the parameters listed in Table 1.

Table 1. List of key specific processes and parameters to monitor EWE (See brief definitions in Annex 4).

Process	Aim/output	Tools (examples)
Heat Fluxes (HF) between surface and atmosphere	To analyse the energy release and flows between the surface and the atmosphere and its contribution to the later. Although this parameter already exists in some computational methods (e.g. fire simulation models), the discretisation is usually too sparse, which averages the resulting thermal energy, so the results are not useful for monitoring the local effect. For this reason, it would be necessary to consider HF but obtained differently from the way it is currently offered. There is a significant gap in addressing this key parameter.	Models
Entrainment and detrainment	To analyse how it influences the EWE behaviour.	Doppler Lidar, Radar
Change of the conditions of the Atmospheric Boundary Layer (ABL)	To assess their influence on the EWE. Detecting changes in the ABL is necessary to anticipate the possibility of extreme scenarios.	Atmospheric Vertical Profiles
Indraft speed of the smoke plume	To detect the 'extra-wind' pushing the fire. Downdraft is also important but common in non-EWE wildfires, while indraft may be a specific parameter for EWE.	Doppler Lidar, Radar
Fire-atmosphere coupling triggers	At present there is no knowledge of what triggers the coupling effect between the fire and the atmosphere, so it is important to develop a good understanding about what is happening on the ground to be able to detect this process.	Not defined
Parameter	**Aim/output**	**Tools**
Atmospheric vertical profile from inside the fire smoke plume	It is necessary to obtain measurements of the smoke plume parcel of the fire from on-field. To do this is important to nest the smoke plume with sensors.	Radiosondes (launched inside the influence of the fire behaviour)
Conditions of the Atmospheric Boundary Layer (ABL)	*See 'processes' in this table 'Change of the conditions of the Atmospheric Boundary Layer (ABL)'.*	
Flammability of the landscape [NOTE 1]	There is a need to improve the actual data collection and to determine how this parameter can modify the behaviour of the wildfire (plume, fire growth, etc.). At the moment, current predictions do not give the information needed for these parameters and time periods.	Not defined
Moisture outside the fire	The existent moisture outside the wildfire (in the upper troposphere) can play a role because, even if the atmosphere is stable, it could lead to an unstable situation. This situation can be detected with radiosondes launched close to the fire	Radiosondes (launched outside the fire but near the area)

Process	Aim/output	Tools (examples)
	but out of its influence. The analysis of this parameter may help to assess the maintenance of the pyroconvection. Outside the fire means outside the zone of influence of the fire (ex. Outside the fire column, fire environment, etc.).	

[NOTE 1] Flammability of the landscape: See Annex 1.

Not defined: No specifically developed tools were mentioned during the work sessions to measure this parameter.

CNRS specifies that Table 1 illustrates processes that, are depicted in a coupled fire-atmosphere simulation and can be inferred from Radar/Satellite utilizing indirect observations. However, there remains the challenge to diagnose, represent or obtain these processes and parameters in a manner for decision-making.

4. Tools for acquiring EWE key atmospheric data

Radio Detection and Ranging (RADAR)

Radio Detection and Ranging (RADAR) is a technology that utilizes radio waves to detect objects and measure the range, angle, or velocity of those objects. They can be fix or mobile. Mobile radars enable to perform spatial-temporal analysis which is crucial to distinguish macrophysical characteristics of the smoke plume from near the fire. It is important that radars have the optimal coverage possible and are of a type that permits them to be relocated to different places.

Having numerous radars dispersed across several countries with mobile radars on top of fast-moving vehicles can be highly expensive and should be contemplated prior to planning this type of on-field campaign (fieldwork). Radar can be a solution for gathering real-time data on the ground, yet it has some constrains to consider:

– High cost of the RADAR (S-Band, C-Band, X-Band) and high cost of training people on the use of the RADAR. Specialized individuals are needed to operate RADAR. Along with the cost of the radar, an important element to consider is the availability of a team that can operate and understand the data to transform it into information.

– Field deployment capability: C-Band Weather Radars are affixed to a specific site; hence they cannot be conveniently relocated to a desired allocation where the EWE is occurring, both due to their fixed placement on the ground and their bulky size. They can capture smoke plumes and similar data.

Image 3. Example of mobile radar. NOAA X-POL radar used to study tornadoes, hurricanes, dust storms, winter storms, mountain rainfall, and even swarms of bats (Source: https://www.nssl.noaa.gov/tools/radar/mobile/)

Fire-atmosphere coupled models

High-resolution fire-atmosphere coupled models can be of use but only if they address the key parameters and behaviour of the EWE.

The implementation of a coupled fire-atmosphere model requires:

1. Fuel model data. When addressing these types of maps, it must be considered that depending on the process to be examined, the required resolution may vary. Therefore, for surface models or the analysis of global parameters or processes, resolutions of hundreds to 1 km may suffice. But when it is necessary to introduce the physical processes that involve these phenomena (EWE), it may even be necessary to go down to meters or less (in the case of microphysics).
2. Meteorological knowledge, coupled fire-atmosphere models and real observation data: To capitalize on the data which can already be acquired (Table 5, Table 6), it is necessary to also possess meteorological knowledge. This knowledge is essential to recognize the environmental circumstances that are conducive for the development of pyroconvection. The meteorological forecast can assist in anticipating when and where the meteorological conditions will be favorable for a wildfire to evolve into an EWE (with pyroconvection and deep pyroconvection). However, it is also crucial to have coupled fire-atmosphere models and real observation data to validate them. Within FIRE-RES (WP5) readily available forecasts will be provided.
3. A fast model response system: Once a wildfire ignites, it is vital to activate the implementation of the system, such as the fire-atmosphere coupled system, so it can offer the added benefit of forecasted data of the expected fire behavior. However, it is also crucial to convey the linked uncertainties of the procedure to the teams operating in the field. Presently, this type of model is available in real time as weather forecasts from 12 to 24h that can be frequently updated to take into account the latest 3 hours of observation. Nonetheless, they are not real-time models in the sense that they do not deliver immediate responses right after an alert. Probabilistic forecasts currently require a couple of hours to obtain results but can be updated indefinitely. These coupled fire-atmosphere models are actually used in some

regions (e.g. California, EUA) but they need some adaptation to the requirements of operational decision-making.

5. General criteria for monitoring EWE key parameters

The essential parameters that are outlined in Table 1 are regarded as fundamental components necessary for comprehending and forecasting extreme fire behavior at present. These parameters play a crucial role in enhancing the capacity to have better models to understand how these interactions occur.

Presently, there exist solely two methods for acquiring such data:

a) The coupled fire-atmosphere models (e.g. they are used in France but also operationally from NOA supporting the Hellenic Fire Corps over the past 3 years).
b) On-field observations (e.g. radiosondes, surface mobile weather stations)

Parameters highlighted in Table 1, such as the heat fluxes facilitating surface-atmosphere interaction that initiates fire-atmosphere coupling, plume profile characteristics, and the entrainment and detrainment of dry air or moisture, are linked to coupling phenomena. However, these observations are hard to get on the field from first responders or firefighters due to the extreme conditions that exist in the area where these data must be collected. Therefore, a viable and presently accessible approach to data acquisition involves remote sensing techniques Light Detection and Ranging (LIDAR) or weather Radio Detection and Ranging (RADAR).

A noticeable trend in recent years favors the utilization of weather RADARs to gather comprehensive information because the models have limitations, even the coupled fire-atmosphere models, so the information that they provide is of limited value because they need to be adapted or designed from the beginning, considering the characteristics of EWE behaviourUsers of this information must acknowledge and comprehend the associated limitations and the uncertainties.

As depicted in FIRE-RES D1.1. Transfer of lessons learned on extreme wildfire events to key stakeholders, "*simulators are still not powerful enough to run coupled simulations involving real-time fire adjustments. For decision-making it is necessary to be able to adjust operative models as much as possible to reality. But in the actual models, the basic equations do not adequately consider the behavior of the fire because they are based on the assumptions that do not correspond EWE behavior (Finney et al., 2012). Then the physics of fire behavior in the model does not correspond to reality, and this is mainly because the function of the EWE is still unknown*." D1.1 also accentuates that "S*ome models can be useful with some wildfires and situations, but they cannot predict all the necessary elements for EWE, and the ones that are best suited for that have the disadvantage of the time they take to do so (hours)*."

For instance, the *in-draft* speed of the plume is the extra wind that initiates and propels the fire, nevertheless, this *in-draft* is essentially the consequence of the fire-atmosphere coupling. Acquiring data on the ground does not entirely resolve the issue either, due to the complex interaction involved, such as the positive feedback loop that arises when the fire alters the atmosphere and subsequently the atmosphere reacts and modifies the fire.

While it is plausible to obtain certain data using radiosondes (e.g. wind speed and direction at different atmospheric levels, temperature and relative humidity, altitude of the radiosonde, ascent rate, distance radiosonde-receiver, % signal reception, dew point, atmospheric pressure, GPS position and track), unfortunately currently there is no means to obtain data regarding the generation of transport phenomena like rotational vortices or the whole column rotation, which are exceedingly crucial for the security of the crews' operations in the field. Hence, there is presently a substantial focus on models to provide this data.

Furthermore, there is not a shared common information repository at the European level with on-field observations concerning EWE so that any individual in need of it can access the database and download it for analysis or use. Consequently, in the absence of such a platform, the data acquisition must be conducted using RADAR or LIDAR.

6. Proposed methodology for monitoring EWE

The suggested approach for monitoring EWE does not deviate from the monitoring of other wildfires in terms of procedures. EWE monitoring entails observing some parameters in the same manner as it is done for other wildfires but also adhering to certain specific ones due to the behaviour and traits of the EWE. This is the main reason why in this deliverable special attention is paid to the EWE key parameters.

In this section 6, the EWE monitoring methodology is expounded.

This deliverable 1.4 is not purposed to delineate the general methodology of forest fire analysis. This is already described in other documents such as the *Guidelines of fire analyst competencies and skills* [Castellnou et al., 2021]. The *Guidelines of fire analyst competences and skills* does endeavour to elucidate a singular and specific methodology to be pursued to develop competencies in forest fire analysis, but rather to encompass diverse ways to accomplish the same fire analysis action. However, in the instance of this deliverable, it is selected as a foundation for adapting it to EWE monitoring.

Therefore, from the standpoint of the approach suggested, this deliverable 1.4 (IA1.2) complements section 4.3.2 Description of fire analysis and assessment tasks of the *Guidelines of fire analyst competences and skills* of the AFAN project. So, the part explained in the mentioned *Guidelines* will not be reiterated here in deliverable 1.4 (IA1.2). But we encourage the reader to refer to the *Guidelines of fire analyst competences and skills* for the indicated section.

In the current document, solely those distinguishing points to contemplate that pertain specifically to EWEs are encompassed and denoted in Table 2. Therefore, what has been carried out is to adjust the existing methodology to the EWE, incorporating the monitoring of the key parameters and processes denoted in Table 1.

Table 2. Steps and parameters to include in a general wildfire analysis methodology adapted to EWE with currently available parameters.

Weather/atmospheric analysis

Weather atmospheric analysis to understand the situation of the day and assess the existence of conditions that could potentially favour the development of EWEs. It will specifically include:

1. Analysis of the general synoptic situation to identify conditions favourable to convection: including analysis of the temperatures, relative humidity, wind, etc.
2. Analysis of the vertical atmospheric forecast to identify unstable conditions that may favour PyroCb generation (Skew-T, etc.). Identify boundaries and heights of atmospheric layers to predict the rise of air mass in the troposphere (Figure 16).
3. Evolution of the state and changes in the atmosphere (moisture inputs, etc.) that make foresee a contribution to the fire that creates the conditions for a PyroCb.

EWE behaviour analysis

Monitoring the wildfire once it has started by observing the fire behaviour, runs, pulsations, rotors, smoke plume, PyroCu process, etc. It will specifically include:

1. Temperature, humidity, etc., obtained with radiosonde launching to confirm the model forecast on-field and smoke plume data.
2. ROS: rate of spread >50 m/min. This parameter can be measured on-site through the emergency responders that are in place.
3. Spotting distance >1 km and exhibiting prolific to massive spotting based on Tedim et al. 2018). This parameter can be measured on-site through the emergency response operations that are on-field.
4. Extreme growth of rate (surface per hour, ha/h) values. This parameter can be measured on-site through the emergency responders that are currently on-field.
5. Smoke plume monitoring to observe if it shows elements that make us think that we are in front of an EWE [Castellnou et al., 2022].
6. Fire line intensity 10.000 kW/m (FLI): It is not currently possible to measure this parameter on-field. High fire line intensities (FLI) can trigger fire-atmosphere interaction, producing more extreme and often unexpected fire behaviour. But this value can be estimated with modelled and real measured fire ROS using Byram's equation [Castellnou et al., 2022].

The points 1 to 5 of the 'EWE behaviour analysis' are the parameters that currently allow us to identify an EWE if we rely on the definition. Therefore, when they exceed the values indicated in the definition, they usually result in fire behaviour exceeding the technical limits of control.

In case key parameters such as those indicated in Table 3 are available, the methodology from the *Guidelines of fire analyst competences and skills* could include the aspects described in Table 3 adapting the process of analysis to EWEs.

Table 3. Steps and parameters or processes to include in a general methodology for analysing wildfires adapted to EWE considering parameters of Table 1.

Weather atmospheric analysis
1. Vertical profile from inside the fire.
2. Analysis of the moisture outside the fire.
3. Monitoring the change of the conditions of the atmospheric boundary layer.
4. Identification of the fire-atmosphere coupling triggers.
EWE behaviour analysis
1. Analysis of heat fluxes between surface and atmosphere for energy measurements to calculate the capacity to develop EWE behaviour.
2. Analysis of the flammability of the landscape.
3. Analysis of the data about the entrainment and detrainment of the parcel inside the column.
4. Analysis of the indraft speed of the fire smoke column.
5. Identification of the fire-atmosphere coupling triggers.

Although the methodology proposal was elaborated after the work session on the basis of the information gathered during the sessions, Tables 2 and 3 were not agreed during the working sessions. Therefore, those attending the sessions are not directly responsible for their content. The tables should be taken as a proposal to be tested in future work.

A critical element of the methodology is the depiction of how the data is collected. Significant aspects to ponder are delineated below.

It is imperative to strike a balance between what is robust at the research level and what is imperative at the operational level. Currently, it is feasible to forecast whether the circumstances to develop an EWE exist in case of an ignition emerge. This is to identify if the day has the potential to give rise to an EWE due to the prevailing atmospheric conditions. However, there is no capacity to predict where and when the EWE may occur. Furthermore, there is also no precise data accessible on for example the entrainment and detrainment of the parcel, what occurs upon entering the plume or how they influence it, and other important key parameters specific distinct to EWE concerning the behaviour and mechanisms involved.

It would be advantageous to compile as much information as possible with the aim provide comprehensive catalogues and extensive historical series of EWE occurrences. Nevertheless, it is not reasonable to postpone until this becomes accessible, because as organisations, citizens, emergency managers, etc., it is crucial to be resilient to the EWEs that could emerge presently, hence it is imperative to collect the available data, even if it is limited, and to scrutinize the data already in existence from prior EWE. Concurrently, efforts can be made to amass data, yet it is crucial to operate now with the data at hand, even if it is scarce statistically. Therefore, it would be beneficial to tackle three lines of work in parallel:

1. Collect and analyze information on the ground.
2. Understanding of the EWE phenomena.
3. Providing operational solutions for the next fire season to reduce uncertainty on-field.

Actions on data collection should be developed at short- and long-term since response to next fires needs to be fast in order to avoid personal and environmental losses as seen in previous EWEs.

Long-term requirements (future):

- Catalogues collecting a significant amount of data and systematically collect the recurrence of these events.
- Landscape conditions parameters: identify landscapes that are highly flammable to assess potential for fire-atmosphere coupling during an EWE.
- Atmosphere conditions.

Short-term requirements (next fire season):

- Operational information (information adapted to the needs of decision making for the next fire season and to the quick timescales required, both for the emergency response).
- Monitor key parameters already available (See Table 6). As explained earlier in this document, these parameters may not be the most specific for monitoring EWE but may be useful in some respects while the others (Table) are not available.
- Give a strong impetus to increase research efforts and observation of key parameters that are directly related to EWE in order to test them as soon as possible. It is urgent to start collecting EWE key parameters data. Prioritise data collection over data excellence or data amount, in order to start working on knowing the processes and understanding EWE through a ‘learning by doing’ without delay.

7. Providers of key parameters for EWE within the FIRE-RES project

Existing challenges

During the initial workshops of the FIRE-RES Project, a number of challenges related to IA 1.2 to increase resilience to EWEs were raised and on the basis of these, guidelines were given to address the challenges, as outlined below:

Challenges (Section Extreme Wildfire Event, p.31) identified in D1.1:

1. '*Key variables to identify and predict risk scenarios in order to make operational decisions are essential. A better understanding is needed on growth patterns both feeding and resulting from pyro convective events*'.
2. '*The capacity to collect real time data both at an appropriate scale, and also vertically in the atmosphere*'
3. '*To put the focus on predicting the moments of change*' in wildfire behaviour.
4. '*To have operational capacity to anticipate extreme wildfire behaviour*'

Guidelines identified in D1.1 (Section Extreme Wildfire Event, p.33-36). The summary points included in the same document (Summary of guidelines – EWE) are included next:

Key variables to identify and predict scenarios:

- ✓ *EWE appears with little wind and a lot of humidity.*
- ✓ *In pyroconvective episodes, ambient humidity triggers extreme fire behaviour.*
- ✓ *Extreme fire moments happen at night.*
- ✓ *There is a need to focus on what is unexpected.*
- ✓ *It is also important to find how much energy will be transferred from the fire to the kinematic of the fire plume.*
- ✓ *The Growth rate (ha/h) and ROS are key variables to describe the extreme fire behaviour and growth patterns of these fires*.

There is an urgent need for better monitoring and early warning of the potential for extreme wildfires [Giannaros, et al.; 2022]. Therefore, the continuous monitoring of the conditions that promote extreme fire behaviour is imperative to improve the capacity for coping with extreme wildfires [Giannaros, et al.; 2022].

Parameters provided by FIRE-RES project

Table 4 shows the list of FIRE-RES partners with Innovative Actions that can provide data for the key parameters. In those cases, where output is not directly provided, the work that aims to contribute to the output has been indicated.

Table 4. List of FIRE-RES partners with Innovative Actions that can provide data for the key parameters.

Process	Who will provide it?
Heat Fluxes (HF) between surface and atmosphere	Although this parameter will not be directly addressed, VTT is developing (IA5.4) physical modeling and simulation of fire processes, which results in heat release rate, heat transfer and fire spread, i.e. FLI, heat flux and ROS, but only for fuels for which there is available suitable data, which for now are not available from LL areas, but only from the literature. Furthermore, modeling development is at such an early stage that it cannot yet be applied in real-time models/systems; the calculations take a long time, which also limits the size of the models used, i.e. in practice it is not feasible to do regional modelling/simulation, but only local and smaller ones[2].
Entrainment and detrainment **Change of the conditions of the Atmospheric Boundary Layer (ABL)**	CNR (IA 5.2) computes explicitly and dynamically vertical wind speed above the fire and turbulence at every atmospheric level with the aim to contribute to diagnose entrainment or ABL modification.
Atmospheric vertical profile from inside the fire smoke plume **(radiosondes data)**	CFRS has carried out measures with radiosondes in order to test for this deliverable. Other living labs could be consulted to obtain these data through the response teams of their regions, if they use the radiosonde tool.
Flammability of the landscape [NOTE 1]	TSYLVA has calculated Dead Fuel Moisture (DFM) and Life Fuel Moisture (LFM) for the FIRE-RES living labs and can provide the data.
Moisture outside the fire	CFRS has carried out measures with radiosondes in order to test for this deliverable. Other living labs could be consulted to obtain these data through the response teams of their regions, if they use the radiosondes.

[NOTE 1] Heat fluxes: See annex 1

TSYLVA is providing two different approaches to address the EWE including convective fires within FIRE-RES project:

- The index Extended Attack Assessment Index (EAA): EAA quantifies the fire activity potential over the territory aiming to assist operational decision-making to

[2] The paragraph in italics was clarified after the meeting by email.

reduce fire threats and risks. EAA allows agencies to easily analyse the short-term fire danger that could exist across the service territory and better communicate the wildfire potential on any given day and time, promoting safe and reliable operations. EAA is based on different parameters such as fuels, drought, meteorology, physiological response of fuels to environmental conditions, as well as instability conditions or the probability of occurrence of convective conditions. We calculate this index up to 7 days in advance every 3 hours, so fire agencies are aware of these adverse weather scenarios in advance.

- Empirically-Adjusted simulations based on potential of convection: under the FIRE-RES project we analysed how atmosphere stability may impact the rate of spread (ROS). We found relationships between ROS and convective variables such as Lifted of Convective Flag. The FIRE-RES simulator will adjust the simulations based on potential of convection.

8. Parameters to be provided in future research

At the moment of writing this deliverable, radiosondes are the only available tool within the project, as indicated in Table 1, thereby rendering Table 3 inapplicable directly. Consequently, non-specific parameters have been incorporated into this deliverable to monitor EWE, albeit they are commonly used for monitoring wildfires in general that are not specifically EWEs. Despite their limitations in directly targeting the fundamental drivers and mechanisms that allow understanding and predicting EWE, these parameters can serve as a temporary monitoring solution until the crucial processes and associated parameters can be quantified.

It presents a viable approach that can be implemented within the project framework; however, it is important to emphasize that the methodology outlined in Section 3, encompassing the key parameters included, should be the one to apply if we want to address EWE specifically.

The list of key processes and parameters to be provided in the future:

a) Processes:

- Heat Fluxes (HF) between surface and atmosphere
- Entrainment and detrainment
- Change of the conditions of the atmospheric boundary layer (ABL)
- Indraft speed of the smoke plume
- Fire-atmosphere coupling triggers

b) Parameters:

- Atmospheric vertical profile from inside the fire smoke plume
- Fire-atmosphere coupling triggers
- Moisture outside the fire

9. Current EWE monitoring

Since the full methodology that it is proposed in this document (Section 6) cannot be applied yet because there is neither the necessary data nor the information on key variables and processes available, it is proposed to focus on following up the parameters that already are available.

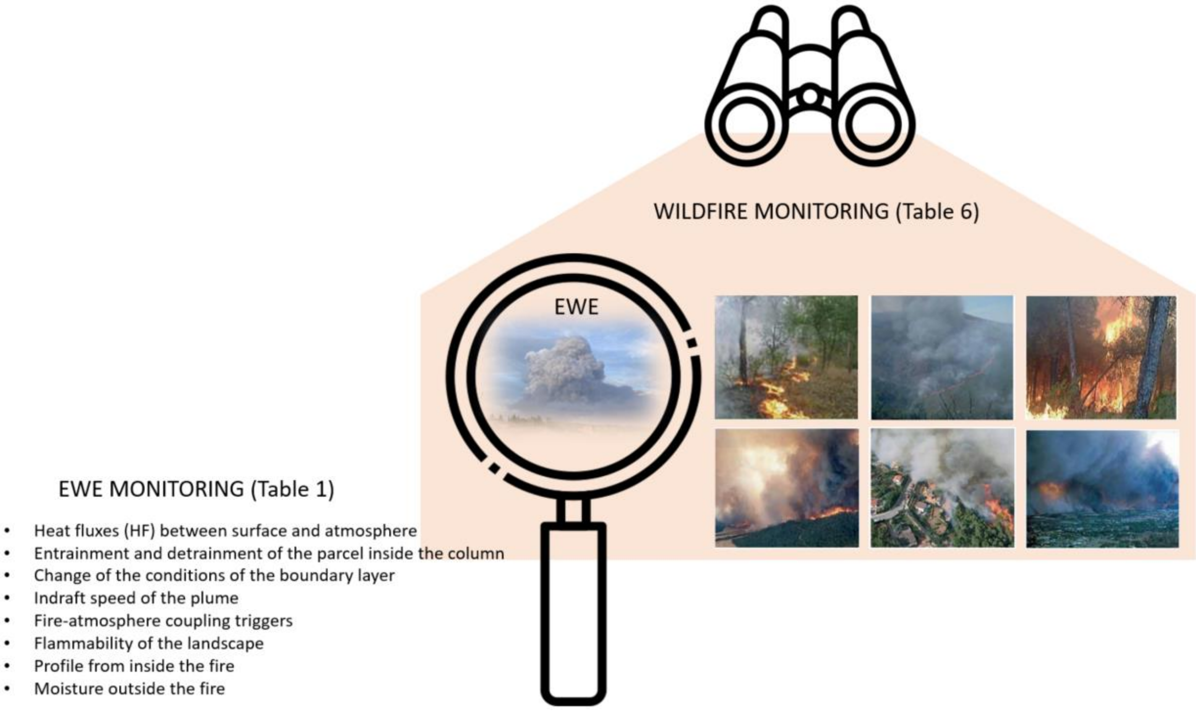


Figure 2. Table 1 vs. Table 6 parameters.

Parameters currently used to monitor wildfires

Table 5 shows the type of parameters that are currently monitored for EWE tracking and some suggested tools. This table is based to the information compiled during the previous work and first working session from the consulted experts.

Table 5. Types of parameters monitored when anticipating the occurrence of pyroconvection related to 3D structure of the atmosphere and its evolution in time and space.

Parameters	a. Large-scale atmospheric parameters. For example, 500 hPa geopotential height, to highlight (in the medium-range and the mesoscale) periods that are potentially favourable for such (dry and hot) surface fire weather conditions. b. Large-scale atmospheric circulation patterns to identify upper-air disturbances in the upper-level moisture required to trigger elevated convection (e.g. 500-700 hPa moisture and moisture advection). c. The vertical structure of winds. Wind shear is a factor that can hinder the development of pyroconvection. d. Lapse rates and humidity levels. Skew-T can give an overview of the lapse rates and humidity levels at all relevant heights.

	e. Convective available potential energy (CAPE). f. Downdraft CAPE (DCAPE). g. Low Level Shear and Deep Layer Shear (LLS and DLS). h. Basic surface information (temperature and humidity) to get a general idea of the fire behaviour that can be expected. i. Visual atmospheric indicators (on-field images). j. Cloud top temperature and height from geostationary satellites. k. The weak/easy to beat Convective Inhibition (CIN) analysing atmosphere vertical profiles relying on ERA5 reanalysis (one case in forecast) [Artés, T., et al. 2022]. l. On-field atmospheric vertical profile parameters [Castellnou, M., et al. 2022].
Tools	Skew-T plots and Hovmuller (time-height) plots (Example: Fig. 7 from Giannaros, T.M., et al.; 2022. https://doi.org/10.3390/atmos13030475), NWP (numerical weather prediction) models and radiosondes.

For the parameters that can currently be monitored, some requirements that are ideally needed (data, tools and conditions) in order to carry out the measurements were indicated as items to also consider. They are listed next:

- Observations of the 3D atmospheric state at the area affected by a wildfire, not limited to radiosondes but extended to RADAR/LIDAR.
- Data of the smoke plume development to understand the conditions leading the development of pyroconvection (ascending velocity speed, temperature, movement, etc.).
- Regular and continuous atmospheric vertical profile information during the EWE within and outside the plume.
- LIDAR data.
- Data coming from observations or simulation models that includes fireline intensity, which gets translated to heat that goes into the atmospheric profile (translating it into a Skew-T).
- Tools to translate the effect of pyroconvection to surface weather conditions (wind speed, direction, temperature, humidity, etc.).
- Forecasting the ease of occurrence of pyroCb and pyroCu.

List of parameters that can be monitored

Emphasizing currently available parameters is the approach to addressing the necessity for data acquisition while the essential EWE parameters (Table 1) remain unavailable. This represents an interim solution to progressively enhance our understating of EWE.

Nevertheless, the aim of IA 1.2 (D1.4) was not to collect data but to identify the key atmospheric parameters for monitoring EWE and to propose a methodology. However, this section aims to provide a solution in case the key atmospheric parameters for EWE are not available for those who wish to monitor the event.

At present, we cannot forecast when and where the extreme wildfire event will occur. As indicated in D1.1, "*Even though there is a lot of information (indexes, parameters, etc.) compared with the past, we are still unable to predict where, when and for what reason these EWE occur*". It is currently feasible to approximate whether conditions on a given day will favour the potential development of an EWE. However accurately forecasting the exact location of an EWE remains a gap that requires focused efforts. This gap is not narrowed by monitoring the parameters listed in Table 6. Efforts should be directed towards developing the improved methods identified in this report, to enhance the prediction of EWEs.

Table 6 identifies the currently available data and indexes that can be useful while the most appropriate ones are not yet accessible. The typologies identified in Table 6 have been widely utilized, but it is worth mentioning that they are not sufficient to predict the occurrence or behaviour of EWE, which is currently the most significant shortcoming.

Table 6. List of key parameters that are currently monitored for EWE tracking.

Parameter	Type	Aim/output	Tools
Basic surface information (temperature and humidity)	Surface parameters	To get a general idea of the fire behaviour that can be expected.	Weather station information, models
500 hPa geopotential height	Large-scale atmospheric parameters	To highlight (in the medium-range and the mesoscale) periods that are potentially favourable for such (dry and hot) surface fire weather conditions.	Models
500-700 hPa moisture and moisture advection	Large-scale atmospheric parameters	Analysis of the large-scale atmospheric circulation patterns to identify upper-air disturbances in the upper-level moisture required to trigger elevated convection	Models
Wind shear	Vertical structure of winds	Wind shear is a factor that can hinder the development of pyroconvection.	(*)
Lapse rates and humidity levels	Vertical profile data	(*)	Skew-T can give an overview of the lapse rates and humidity levels at all relevant heights.
Convective available potential energy (CAPE).	Indexes	Describes the instability of the atmosphere and provides an approximation of updraft strength	CAPE index
Downdraft CAPE (DCAPE).	Indexes	DCAPE is the maximum energy available to a descending parcel of air and it is used to estimate the potential strength downdrafts. The higher the value of DCAPE, the stronger the downdraft potential.	DCAPE index
Low Level Shear and Deep Layer Shear (LLS and DLS).	(*)	(*)	(*)
Visual atmospheric indicators.	Imagery	(*)	On-field images.
Cloud top temperature and height. [NOTE 1]	Satellites	(*)	Geostationary satellites.

Parameter	Type	Aim/output	Tools
Atmosphere vertical profiles relying on ERA5 reanalysis (one case in forecast).	Vertical profile data	Analyse the weakness/easiness to beat Convective Inhibition (CIN)	Artés, T., et al. 2022.
LFM, DFM in the European living labs	Indexes	Describes the moister content in live and dead matter.	Models
Temperature, Humidity, Velocity, Position.	On-field data (radiosondes)	Understand what is happening in the fire.	Castellnou, M., et al. 2022

[NOTE 1] Cloud top temperature: See Annex: [NOTE 2] Weather data in the atmosphere

(*) Nothing else was commented about the listed parameter during the work session, so nothing else has been included in this table since it is the result of that session.

Tools to monitor and analyse key atmospheric process and parameters for EWE

During the initial work session, the suitability of some of the tools presently in utilization was deliberated. The subsequent are the aspects that were emphasized.

High resolution models

High-resolution models can be a mechanism to utilize but solely if they tackle the key variables and behaviour of an EWE. This implies reconsidering these models that cover different processes. Rather than using the adapted models to provide operational tools on the ground, it is important to work the other way around, obtaining data on the ground to develop new models that look at key parameters and EWE specifically.

Remote sensing

The need for tools to measure from the ground, not from afar, was identified. Current remote sensing tools are reaching their limits for predicting these EWE and although some increase in resolution can be aspired to, it is difficult to derive local implications from these remote data. Basically, two key data collection tools are proposed for EWE: terrestrial LIDAR and radiosondes.

Satellites

It is difficult to obtain data in an optimal time range to make operational decisions during EWE occurrence and therefore they are often not a sufficiently adequate real-time (e.g. < 3 hours) monitoring tool, except for geostationary satellites. This will probably be improved in the future, but they seem not to be the best option at the moment.

General criteria for monitoring EWEs with the available tools and data

Whatever tools are used in monitoring EWE they should meet the following 3 criteria:

1. Availability to monitor during the fire-atmosphere coupling: Making an effort to measure parameters when the fire is coupled with the atmosphere is key.
2. Capacity to transforming data into operational information: Translating information (e.g. the speed to the plume, this is the 'extra-wind' pushing the fire; the change of the conditions of the boundary layer; the atmospheric process that unfold pyroconvection) into operational parameters (e.g. increase of ROS, etc.) is important to be able to make decisions as to evacuate or confine.

   Some indexes as Fire Weather Index (FWI) can be confusing. An important point to note about the indicators is that it is not necessarily an extreme FWI that will generate the convective cloud. For example, in summer (end of 2022) there was an Extreme FWI in Biobio region in Chile and the index worked fine for wildfires driven by wind. However, for fires with more convective activity, these models do not necessarily show extreme values because the interaction with the topography is not included in them, and we observed that the greatest convective activity was in fires with less heavy vegetation but with great topography interaction[3].
3. Use of standards for data collection: It would be important to define minimum standards for the collection of on-field data so that they are comparable across different EWE sites.

Providers of non-specific parameters for EWE that are actually available within the FIRE-RES project

Within the FIRE-RES Project there are IAs and partners that address the parameters listed in Table 7.

Table 7. List of key parameters that are currently monitored for EWE tracking.

Parameter	Who will provide it?
Basic surface information (temperature and humidity)	FIRE-RES Integrative system WP5: *IA5.1. Integrative umbrella system for EWE decision-making* [NOTE 1]

[3] Comment on chat by Jorge Saavedra (CONAF) who during the discussion had problems with the on-line connection.

Parameter	Who will provide it?
500 hPa geopotential height	FIRE-RES Integrative system WP5: *IA 5.5. Earth Observation data collection to support decision-making* [NOTE 1]
500-700 hPa moisture and moisture advection	No partner within the project provides this data directly. If necessary, external sources should be consulted.
Wind shear	FIRE-RES Integrative system WP5 IA5.5. [NOTE 1]
Lapse rates and humidity levels	Not defined yet at the time of writing this deliverable.
Convective available potential energy (CAPE)	FIRE-RES Integrative system WP5 IA5.5. [NOTE 2]
Downdraft CAPE (DCAPE)	FIRE-RES Integrative system WP5 IA5.5. [NOTE 2]
Low Level Shear and Deep Layer Shear (LLS and DLS)	No partner within the project provides this data directly. If necessary, external sources should be consulted.
Visual atmospheric indicators	Practitioners can be consulted.
Cloud top temperature and height (SEE NOTE 2)	The ISS platform (IA5.1) should be able to provide a layer from EUMETSAT of the cloud top height. (SEE NOTE 2)
Atmosphere vertical profiles relying on ERA5 reanalysis (one case in forecast)	No partner within the project provides this data directly. If necessary, external sources should be consulted.
	TSYLVA will provide the following weather variables for the surface weather data through the generation of the high-resolution WRF weather: • DCAPE: Downdraft convective available energy. • LCL: Lifting Condensation Level. • NCL: Free Convection Level. • EL: Equilibrium Level. • TCON: Convective temperature / Triggering temperature / Release temperature. • CCL: Convective condensation level.
Temperature, Humidity, Rate of Spread (Velocity), Position of the EWE, Wind, Speed, Wind gust.	No partner within the project provides this data directly. CFRS can be consulted on their measures.

[NOTE 1] & [NOTE 2] See Annex 1

10. Innovative Action 1.4 implementation

IA1.2 is intended to be implemented in all living labs wherever an EWE occurs throughout the project's duration. The implementation of this IA necessitates the presence of necessary tools and the measurement of identified parameters. Additionally, it also requires the existence of wildfire analysis teams (as explained in the Guidelines of fire analyst competencies and skills, 2021) capable of comprehending the acquired data and translating it into decision-making tools.

At the present time of drafting this deliverable, only the parameters of Table 1 that can be derived from radiosondes are accessible within the FIRE-RES project. At the time of writing this deliverable, the test using radiosondes has been conducted in Chile (2023 fire season) and Catalonia (2022 fire season).

Annexes 2 and 3 expound upon the tools and parameters utilized, as the objective of this deliverable is not to elucidate the phenomenon or the Chile 2023 wildfire campaign, but to exemplify the application of a currently feasible part of the methodology through implementation.

This deliverable provides details on parameters that, while not specific to EWE, are presently utilized for wildfire monitoring purposes. This can facilitate the monitoring of EWEs throughout the project until tools for monitoring the pivotal parameters outlined in Table 1 become available.

Nevertheless, the enumeration in Table 1 is of paramount importance as it outlines the key parameters that need to be monitored to address EWE. If ultimately unfeasible during the FIRE-RES project to monitor the specific parameters of EWEs, it can be used in future projects or endeavours.

Concurrently with FIRE-RES, two other projects are tackling the issue: EWED[4] and NERO[3].

In the EWED project (2024-2025), atmospheric data will be gathered using radiosondes to collect fire and atmosphere data from extreme wildfire behaviour that could escalate into extreme events in European countries (Norway, Spain, Greece, Netherlands, among others). These data will be used to populate a novel Open Data Portal. The intricate processes involved will be adjusted based on Large Eddy Simulation (LES). The outcomes will be used to improve a land-atmosphere coupled model (CLASS) to learn and improve the comprehension of the atmosphere-fire feedback during extreme fire events. The resultant model and data portal will enable real-time analysis of ongoing extreme fire events with atmosphere coupling. Ultimately, the findings will contribute to proposing advanced guidelines and training on preparing for and responding to extreme wildfires

[4] See list of acronyms at the beginning of the document.

in Europe. Several FIRE-RES partners are also engaged in the EWED project (Catalan Fire and Rescue Service, Wageningen University & Research) fostering synergies and collaborations, and promoting the adoption of the use of radiosondes in Norway, Spain, Greece, and The Netherlands (https://civil-protection-knowledge-network.europa.eu/projects/ewed) .

NERO is the European Network on Extreme fiRe behaviour (Action CA22164 - COST). The project is led by NOA and aims to cultivate a European culture that fosters effective cross-boundary sharing of expert knowledge, including data and tools. NERO aims to bridge the gap between scientific findings and practical application, advocating for efficient science-based wildfire management. The overarching goal of NERO is to create and coordinate an international network that brings together wildfire scientists and practitioners to address the challenge of understanding and predicting extreme fire behaviour.

Technological Readiness Level

During the proposal of the project, it was envisioned that given the number of organisations and partners involved as well as their capabilities, the challenge of increasing knowledge about the behaviour and parameters of EWEs could be addressed. For this reason, a TRL leap for IA 1.2 from level 1 to level 3 was proposed.

TRL	EU commission description[5]	IA 1.2 application
Level 1	Basic principles observed	Starting level: Before the starting of the project different principles were observed with atmospheric data analysis, using new knowledge and expertise on EWE. On the other hand, experts and operatives had already started to identify key parameters. (This document is not a state of the art but the references at the end of this document serve as examples).
Level 2	Technology concept formulated	Level achieved: Work session 1 and work session 2 were used to determine the key parameters needed to monitor EWE (Table 1). In addition, an adaptation of existing methodologies to address EWE has been proposed (Section 6).

[5] HORIZON 2020 – WORK PROGRAMME 2016-2017 General Annexes. Section G.

TRL	EU commission description[5]	IA 1.2 application
Level 3	Experimental proof of concept	Level partially achieved (1): For the reasons explained widely in this document, the parameters of Table 1 that can be obtained with radiosondes are available within the FIRE-RES project. At the time of writing this deliverable, the test has already been carried out in Chile (2023 fire season) and Catalonia (2022 fire season) using radiosondes. Therefore, this level is considered to have been completed for those parameters that can be collected by radiosondes.

Note (1): As indicated in the Grant Agreement (Section 1.3.2), 'whenever the highest TRL levels cannot be achieved, guidance will be given to facilitate its advancement beyond the project (Task 6.3 Upscaling).

From an emergency response perspective, TRL fall short of what is needed to assess whether a technology, process or tool is ready to be implemented. As it was stated in FIRE-IN project (2017-2022) '*TRL is a good indicator of "operatively level" of tools, but this TRLs are not "suitable" or validated by responders*' (FIRE-IN, D1.3). The FIRE-IN project also remarked that '*It is necessary to develop processes to assess, validate and/or certify the level of TRL and the operative application level of services and tools used by responders (EPIs, models of behaviour, AI, etc.)*' (FIRE-IN, D1.4). But TRL has limitations in terms of considering the level of readiness for an emergency responders' perspective. Therefore, achieving TRL9 does not imply that it is usable at the operational level. Furthermore, the assessment of each level by research, technological or, industry partner could result in a different outcome compared to an assessment carried out by an emergency response organization.

To evaluate the readiness of a technology for employment in emergencies (readiness level), other elements should be taken into account beyond the TRL, which only addresses maturity. Factors to be taken into consideration encompass accessibility, resilience, scale of application, operational resolution capability for the challenge to deal with, usability, current implementation in organisations facing similar scenarios, ease of integration into existing response organisations' own tools, among others. This signifies that, from the standpoint of emergency response arena, it is essential to transcend research readiness and industrial readiness to address readiness from the other crucial perspectives such as standardisation, scale of application or capacity of operative resolution.

11. Conclusions

The key parameters, processes and drivers to monitor EWEs (Table 1) that were recognized in this IA are: heat fluxes, atmospheric profiles from inside the fire, moisture outside the fire, entrainment and detrainment, indraft speed of the plume, the change of the conditions of the boundary layer, fire-atmosphere coupling triggers, and flammability of the landscape. Some of those variables will be addressed within the FIRE-RES project and others will necessitate further investigation (Section 7 and 8).

It is essential to have empirical data accessible on-site to incorporate it into the simulations and to derive outcomes that facilitate comprehension of the behaviour of EWE. However, these models need to address the key parameters that are significant in EWE to enable the anticipation of the EWE behaviour.

The approach for EWE assessment (Section 6) does not deviate from the fire analysis methodology except that it incorporates the specific examination of primary variables and mechanisms particular to EWE.

EWEs can be traced with currently available tools (Table 6), but it is crucial to recognize that this does not encompass all primary aspects for comprehending the EWEs identified by the experts, even though it does permit their tracking and information gathering.

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ANNEX 1. Notes to the tables

This annex includes remarks and rationales from experts and partners for the topics in the tables generated during the two working sessions held for this IA Notes are recognized under the title of the table they pertain to.

Table 1. List of key processes and parameters specific to monitor EWE.

[NOTE 1] Flammability of the landscape.

This parameter was not distinguished as a key one in the initial working session but was mentioned in the subsequent session.

In Portugal, work is underway to improve information about the humidity of the fuels and to obtain data about the flammability of the fuels. At the moment, there is no real data from that sort of parameters. Only forecasts exist for this type of information.

There is a necessity to enhance the current data collection and to ascertain how this parameter can alter the dynamics of the wildfire (plume, fire growth, etc.). By doing so, operatives will be able to advise the crews on the ground on what actions to take and on the behaviour and potential of the fire for the next 3-6 hours.

Present predictions do not provide the required information for these parameters and time periods. Hence, it is crucial to improve the predictions through the integration of field data to understand the events in the forest fire, in relation to the atmosphere and within the fire itself.

Table 6. List of key parameters that are currently monitored for EWE tracking.

[NOTE 1] Cloud top temperature

The cloud top temperature parameter must be obtained through direct observation. This data provides insights on how high the plume is able to deep into the free atmosphere or remains within the boundary layer, so therefore cannot be predicted. There is a need to have this information, which is not available actually for Europe. Europe lacks a geostationary satellite with sufficient resolution to detect the typical fire sizes and gather relevant fire size information. Consequently, on-field observations of large fires must be utilized.

One potential solution is to employ meteorological RADARs to obtain information about how high the plume is going to influence the temperature. Alternatively, it is also possible to launch radiosondes inside the plume and try to get the temperature at the top of the plume. But in any case, it is not as available in Europe as it is in the USA or Australia with their satellite constellations. Nevertheless, Geostationary Operational Environmental Satellite (GOES) does not detect many of the fires.

Important information that satellites can provide refers to what the plume is doing at the moment. From this data it is possible to forecast what the fire will be doing in the next 2-3 hours. Satellites have been proven to be a good tool for analysis after events for considering or adjusting the results. However, the resolution of second-generation satellites currently available in Europe is insufficient for operational needs and consistently lags in monitoring fire behaviour effectively.

[NOTE 2] Vertical atmospheric data

In FIRE-RES project, Spire will provide atmospheric data, forecasted 4 times a day. The simulations at 00Z and 12Z will go out to 15 days into the future whereas the forecasts from 06Z and 18Z will only go out 24 h into the future. Co-funded by ESA, Spire has developed a gridded soil moisture observation product at 500 m resolution. The product will soon be enhanced to 100 m spatial resolution. The ISS platform (IA5.1) should be able to provide a layer from European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) of the cloud top height because it has not been possible to find a layer of the Cloud Top Temperature.

Table 8. List of key parameters that are currently monitored for EWE tracking.

Weather forecast [NOTE 1]

In the D5.1. *Technical requirements and system architecture of the integrative software system section [DM3] Columnar atmospheric weather data* the information to be made available is specified:

Weather forecast of vertical atmosphere profiles up to 20.000 m of altitude in different isobaric levels (i.e., from 1hPa to 1000 hPa). The forecasts will be produced several times per day (at 0:00h, 06:00h, 12:00h and 18:00h UTC), and the following lead times will be made available:

i) 0-h (the analysis of the state of the atmosphere at the beginning of the forecast cycle),
ii) Hourly forecasts until the 48h
iii) 3-Hourly forecasts from 48h to 120h (5 days)
iv) 6-Hourly forecasts from 120h to 240h (10 days)

The variables included will be:

- Geopotential height
- Temperature
- U-wind component
- V-wind component
- Relative Humidity
- Vertical velocity
- Absolute vorticity

- Cloud water mixing ratio
- Cloud ice mixing ratio
- Convective Temperature or Triggering temperature (TCON)
- Convective Condensation Level (CCL)

Within FIRE-RES, WP5 will provide these weather variables (surface weather data) through the WRF high-resolution weather model and visualized as layers in the ISS platform (WP5, IA 5.1. Integrative umbrella system for EWE decision-making) as well as used in the fire simulation models developed in WP5 (Requirements for IA 5.5. Earth Observation data collection to support decision-making, SPIRE vertical weather profiles)[6].

High resolution surface weather models from INRAE & TSYLVA

In FIRE-RES, CNRS will run fire-atmosphere coupled models that will be integrated in the ISS platform (IA5.1) for demonstration purposes. CNRS will run these simulations within FIRE-RES whenever there is a fire in one of the Living Labs (Spain, Portugal, Greece), providing around *100-meter resolution* to have the full coupling process (80 and 150 m resolution) with the fire-line and the fire propagation of the fire included.

TSYLVA runs high resolution model of a *2 km resolution* that can provide some of these parameters for the Living Labs of Canary Islands (only for *Gran Canaria*), Catalonia, Germany-The Netherlands and Portugal.

TSYLVA will run a WRF high-resolution surface weather model based on GFS which provides weather variables that shall be visible through the ISS platform interface. Some of the variables will be used by the fire simulator as well as by the smoke dispersion model from MITIGA (WP5). This weather data will be provided for the following LLs: Portugal, Catalonia, Germany-Netherlands, Gran Canaria[7].

WP5 is running an atmospheric forecast model for some of the living lags, but it is not totally operational at the moment of writing this deliverable. The model will be running on a daily basis.

Other external visual layers/services related with weather variables that will be added to the ISS platform (IA5.1)[8]

- Combined Drought Indicator (CDI)
- FWI - Drought Code (DC)
- KBDI - Keetch-Byron Drought Index
- Soil Moisture
- Precipitation Rate at Ground

[6] The paragraph in italics was clarified after the meeting by email, not during the work sessions.
[7] The paragraph in italics was clarified after the meeting by email, not during the work sessions.
[8] The paragraph in italics was clarified after the meeting by email, not during the work sessions.

- Accumulated Precipitation at Ground
- Snow mask
- Cloud Top Height

ANNEX 2. SUMMARY OF EXTREME WILDFIRE EVENT (EWE) CHILE 2023 (CONAF)

PRECURSORY BACKGROUND OF THE EMERGENCY

Between February 1st and 4th, an extreme wildfire event (EWE) was recorded, which was triggered by the combination of adverse meteorological variables, stress conditions in vegetation, and especially by the simultaneity of pyroconvective events, generated from the synchrony of active wildfires in the regions of Ñuble, Biobío, and La Araucanía.

Meteorology

Table 1 summarizes the maximum and minimum records of temperature, relative humidity, and Fine Fuel Moisture for the regions affected by the emergency.

Annex Table 1. Summary of meteorological conditions at weather stations near wildfires.

Weather station/ Region	Temperature	Relative humidity	Fine dead fuel moisture
Ninhue/Región de Ñuble	Peak of 40.2°C (Between December 2023 - February 2024) During the first week of February temperatures were high with minimum temperatures ranging between 5 and 15°C. This indicated that during the night, the temperature decrease, and moisture recovery were minimal, increasing the risk of wildfires.	During the last week of December 2023, there were low values of minimum and maximum relative humidity. In the first week of February, there were low values of maximum relative humidity compared to the analyzed period. This explains the low level of moisture recovery during the night. On February 3rd, there was a significant decrease in maximum relative humidity.	It presented maximum values between 12 and 23%, with low values highlighted between the last week of January and the first week of February 2024. This was complemented by low records in the minimum fine dead fuel moisture during that period, except for a peak on February 4th (12%).

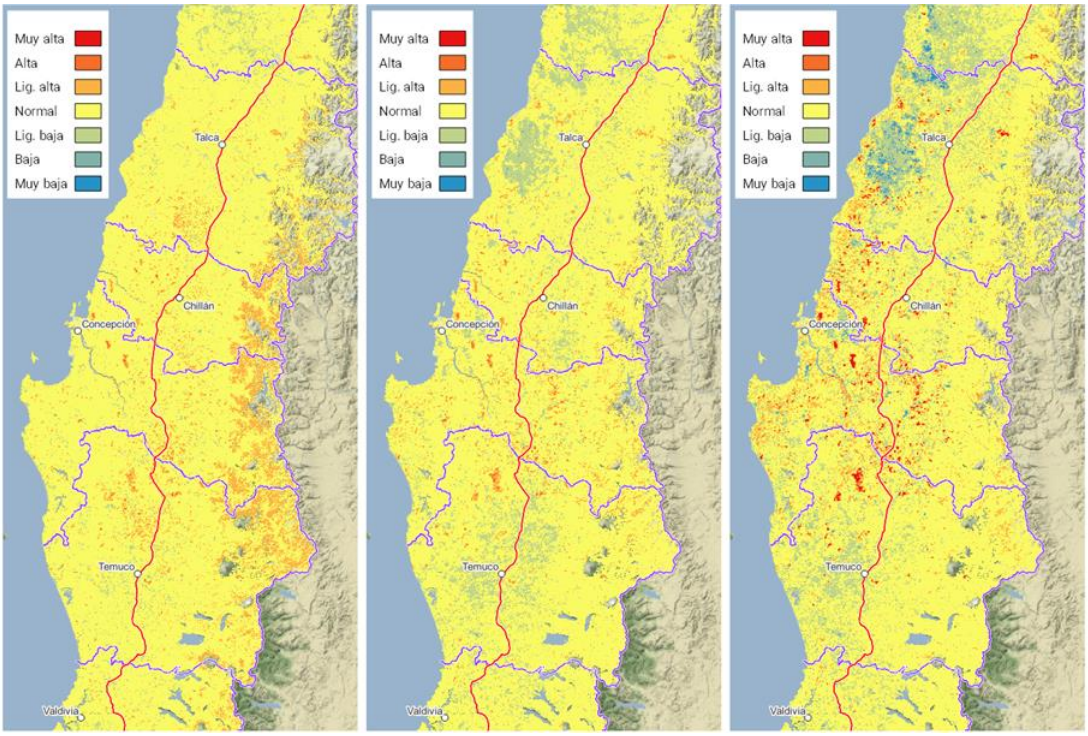
Weather station/ Region	Temperature	Relative humidity	Fine dead fuel moisture
Chiguayante / Región del Biobío	The daily minimum temperatures ranged between 9.6 and 16.4°C from December to February, similar to previous seasons. The maximum temperatures ranged between 16.9 and 37.6°C, with the highest value recorded on February 3rd.	Between December and February, there was significant oscillation, with low values noted on February 3rd and 17th (6.3% and 9.8% respectively). From February 1st to 3rd, there was a decline in the minimum Relative Humidity (HR min). Regarding the maximum Relative Humidity (HRmax), there was a low oscillation during the period (ranging from 62% to 95%), with notable drops observed on December 28th and January 11th.	The maximum Fine Fuel Moisture Content fluctuated between 20% and 25%, except for a couple of records with low values (December 28th and January 11th), while the minimum Fine Fuel Moisture Content showed greater oscillation, with a peak exceeding 21% on December 8th, which correlates with a low occurrence of fires on those days.
La Providencia, Traiguén / Región de la Araucanía	The maximum temperatures peaked on December 25th (35.1°C) and February 4th (38.9°C), correlating with occurrences of 20 and 40 fires respectively.	There was greater oscillation (60% to 98%) compared to other seasons. Between December 21st and 25th, there was a decrease in both RHmin and RHmax, which correlated with an increase in forest fires. Similarly, during the peak of	The Fine Fuel Moisture Content showed less oscillation, while the Fine Fuel Moisture Content exhibited greater oscillation compared to previous seasons. On December 25th and February 17th, there were low values recorded for

Weather station/ Region	Temperature	Relative humidity	Fine dead fuel moisture
		fires on February 3rd, there was also a decrease in both HRmin and HRmax. A similar situation occurred between February 15th and 17th.	both FFMCmax and FFMCmin, correlating with an increase in occurrences on those days.

Fuels

The vegetation condition analysis, based on the Enhanced Vegetation Index (EVI) obtained from MODIS images, revealed critical conditions for the summer season in the territories between the regions of Valparaíso and Los Ríos. In this regard, vegetation categorized in high anomaly classes (indicating higher stress and therefore higher susceptibility to fire) showed lower averages for the index compared to the previous and historical seasons (Figure 1).

EVI season 2022-2023 vs. 2021-2022	EVI 2022-2023 season vs. five-year period	EVI anomaly for the five-year period



Annex Figure 1. Comparative EVI maps July 2022 – January 2023 period.

Additionally, (apart from the Region Metropolitana), the largest proportion of vegetation was in unfavorable conditions (approximately 1.22 million hectares), consisting of forest plantations (41%), followed by grassland (26%) and native forest (17%).

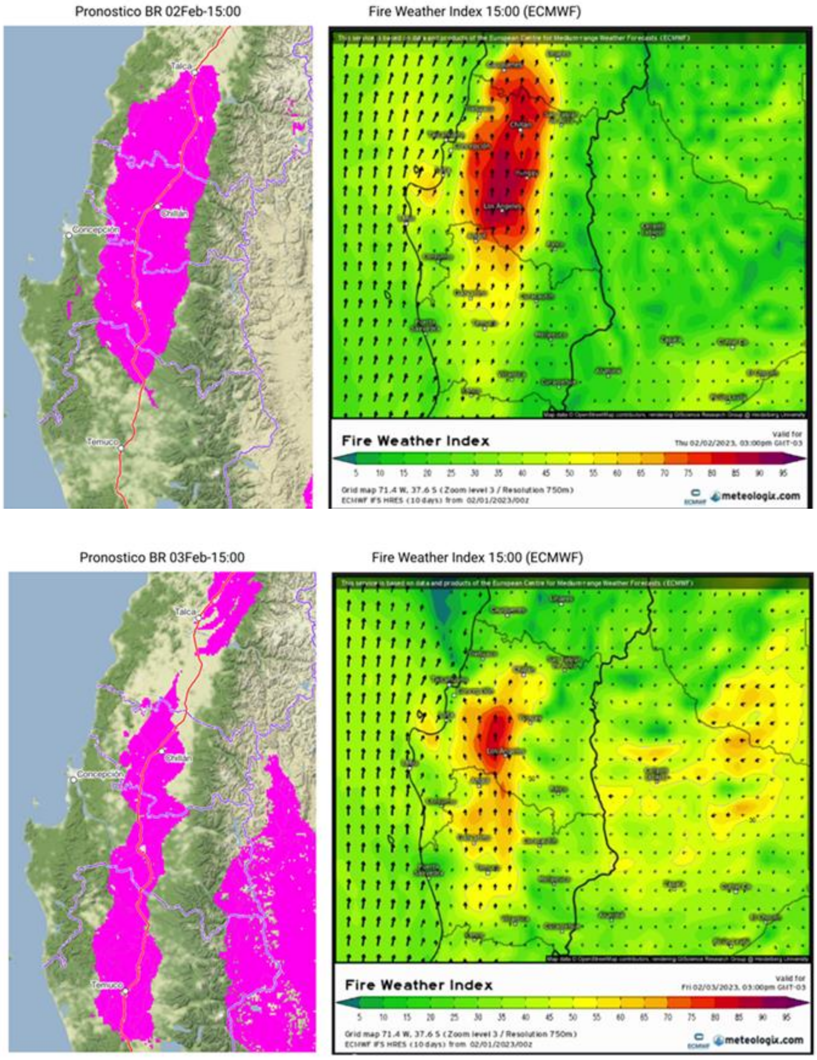
Fuel availability showed increased vigor due to the growth of annual grasses, *gramineae*, weeds, etc., which did not develop in the previous season due to precipitation deficit. Therefore, in 2023 there was a large amount of fine and dead vegetation available for ignition in the central zone and another consolidating its desiccation in the central-southern zone, which configured a greater load of fine and dead biomass favoring the spread of fire from grassland to taller fuels.

Given the aforementioned background, it was determined that the central and central-southern zones would be the most complex during the season, with a high probability of fast and virulent wildfires occurring, along with extreme meteorological events.

Conditions that facilitated the event

1. Simultaneity of pyroconvective events: The main catalyst for the situation was the occurrence of simultaneous pyroconvective events resulting from wildfires.
2. Red Button (CONAF) and Fire Weather Index (FWI) Analysis: Examination of the Red Button (CONAF) and Fire Weather Index (FWI) conditions during the peak dates of impact revealed that the significant fires recorded from February 2nd were located within areas experiencing the most extreme meteorological conditions. These areas had exposure times exceeding 12 hours on February 2nd, covering an extensive

area of 2.3 million hectares. Similarly, on February 3rd, there were reports of 2.0 million hectares affected.



Annex Figure 2. Comparative red button versus FWI for February 2nd and 3rd, 2023.

SIMULTANEITY AND EXTREME BEHAVIOUR DURING EMERGENCY

The meteorological scenario for the first days of the extreme event began on February 1st, with significant cloudiness throughout the coast between the Coquimbo and Maule regions due to the arrival of the coastal trough. There were northwest winds in the morning, shifting to southwest winds in the afternoon, with temperatures ranging between 30-33°C.

The southerly wind on February 1st favored low humidity and the growth of fires such as Quilmo-Chillán Viejo, impacting homes and urban areas. The simultaneity of fires worsened during the day. The most significant fires were Quilmo and Caserío Linares 2 in the Ñuble Region.

Annex Figure 3. Convection column and propagation direction of the Quilmo fire.

Subsequently, on February 2nd, the meteorological scenario began with south winds in a generalized manner. The humidity did not recover between the Región Metropolitana and Ñuble. There was an incursion of the anticyclonic wedge moving southward, generating intense winds of continental and dry origin, with minimum humidities dropping below 10%, in addition to high temperatures.

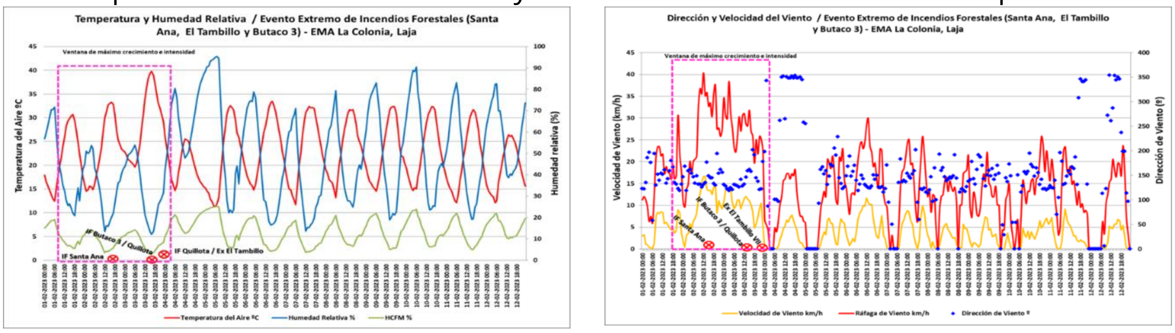
During the night of the 2nd and early morning of the 3rd of February, although there was humidity recovery in many areas, the wind intensified significantly.

On February 3rd, the high-pressure center situated over Chile strengthened and distributed the warm and dry air mass from Argentina northward. The Pacific high pressure was warm and humid, while the high pressure over Argentina was warm and dry. Therefore, from midday, a wind shift was expected, with a significantly warm air mass, resulting in very high temperatures and the inflow of air mass from the Pacific.

Finally, the pressure coming from Argentina had a greater influence than that from the Pacific, which, combined with the significant influence of local winds, topography, and atmospheric dynamics, contributed to the behavior of the fires.

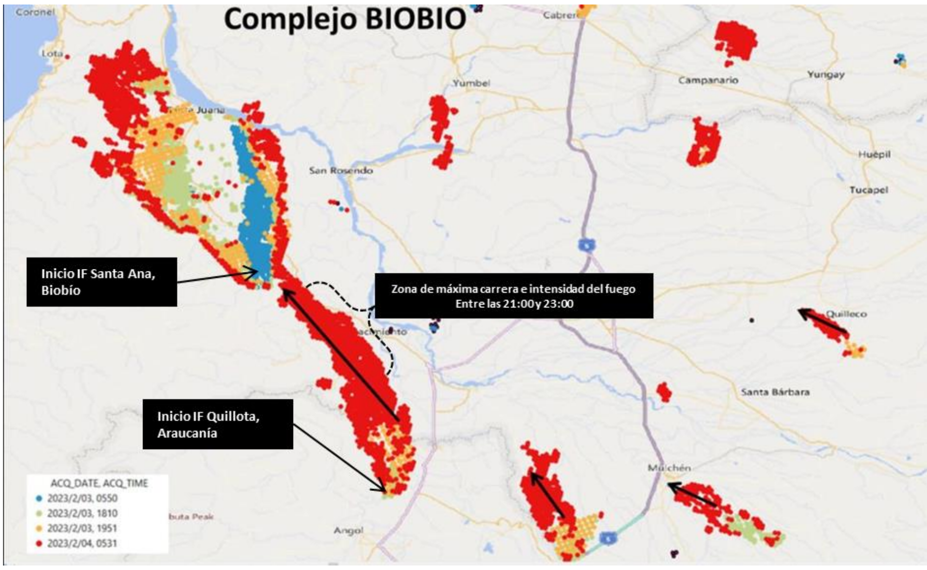
This influence was evident in the Santa Ana - Quillota (formerly Butaco 3) wildfire complex, whereby the end of February 3rd, there was high atmospheric instability. The movement of a low-pressure system along the coast and its inland movement favored the extreme growth of the fires. This was confirmed between 21:00 and 23:00, when the highest rate of spread and intensity of the fire occurred (EUCPT Chile 2023, EGIF-CONAF, 2023).

Temperature and relative humidity — Wind direction and speed



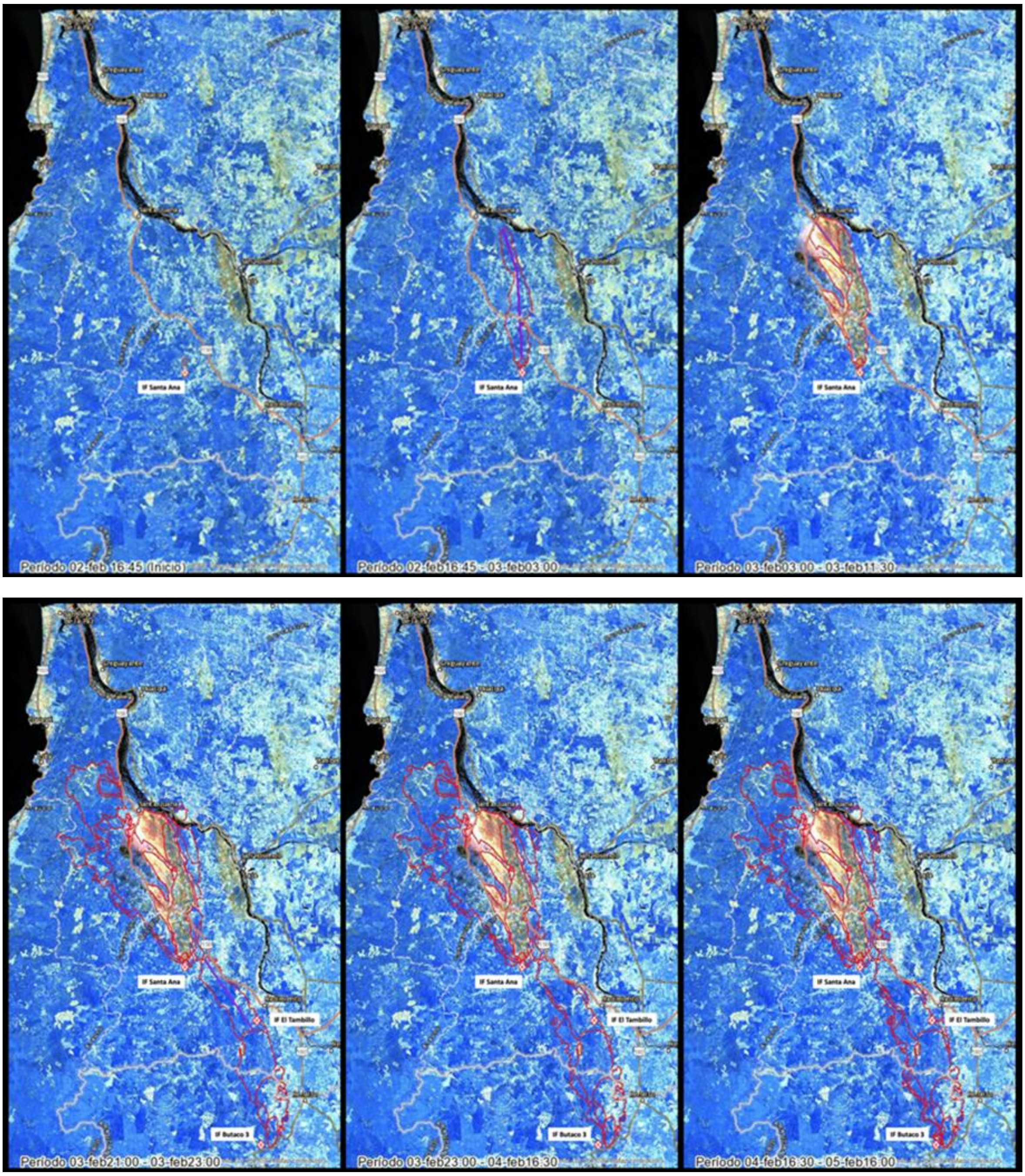
Annex Figure 4. Behaviour between February 1st and 13th.

During this day, the fires continued to grow, but it was the entry of nighttime humidity during the night of February 3rd and early morning of February 4th that led to significant growth of the fires (Figure 4). The Santa Ana fire, located near the coast and therefore one of the first to receive this influx of humidity, experienced the most significant growth and was able to attract the other fires towards it (suction effect).



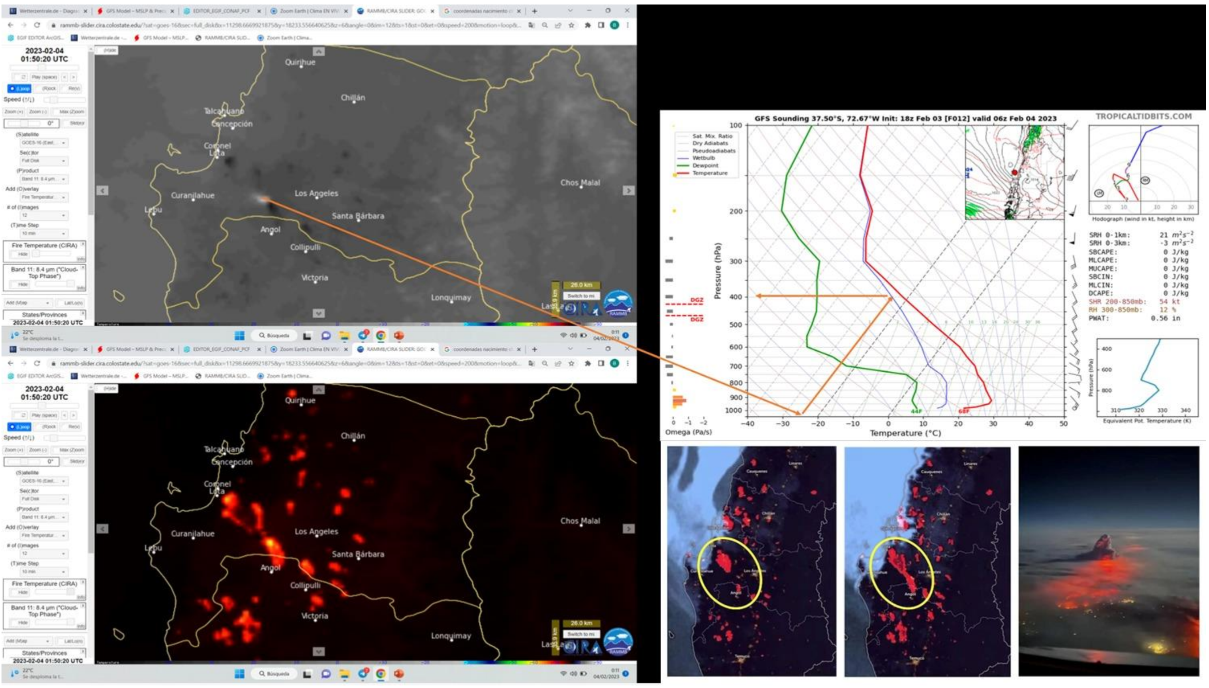
Annex Figure 5. Evolution of VIIRS fire points of the wildfire complex and attraction towards the main fire.

Due to this effect, the Quillota fire (ex Butaco 3) experienced exponential growth with the release of massive secondary fire spots that crossed the Tambillo area in the Biobío Region and reached the southern boundary of the Santa Ana fire (Figure 5).



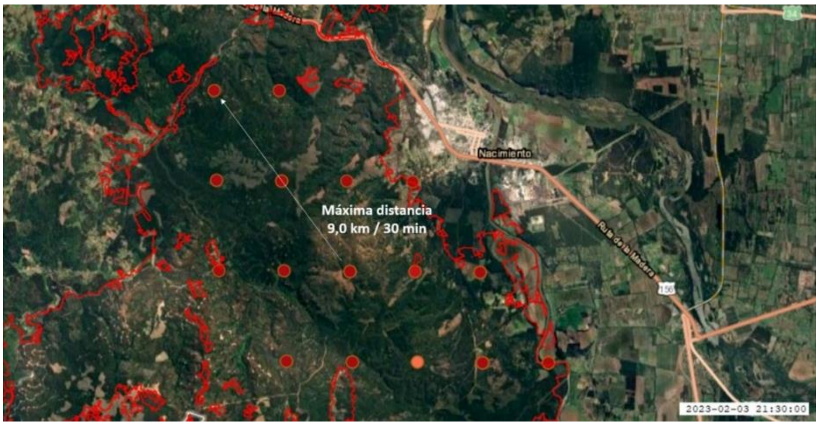
Annex Figure 6. Evolution of the fire complex between February 1st and 4th.

The growth rate of the Santa Ana fire was the highest among all active fires, reaching values of 7,000 hectares per hour and speeds between 15 to 18 km/h. At the perimeter level, it was a fire of over 200 km, with an approximate linear extension of 80 km. The most significant fire run was about 17 km long (between 21:00 and 23:00), of which approximately 9 km were covered in just 30 minutes (Figure 9), between 21:00 and 21:30, equivalent to a propagation speed of 18 km/h or 300 m/min.



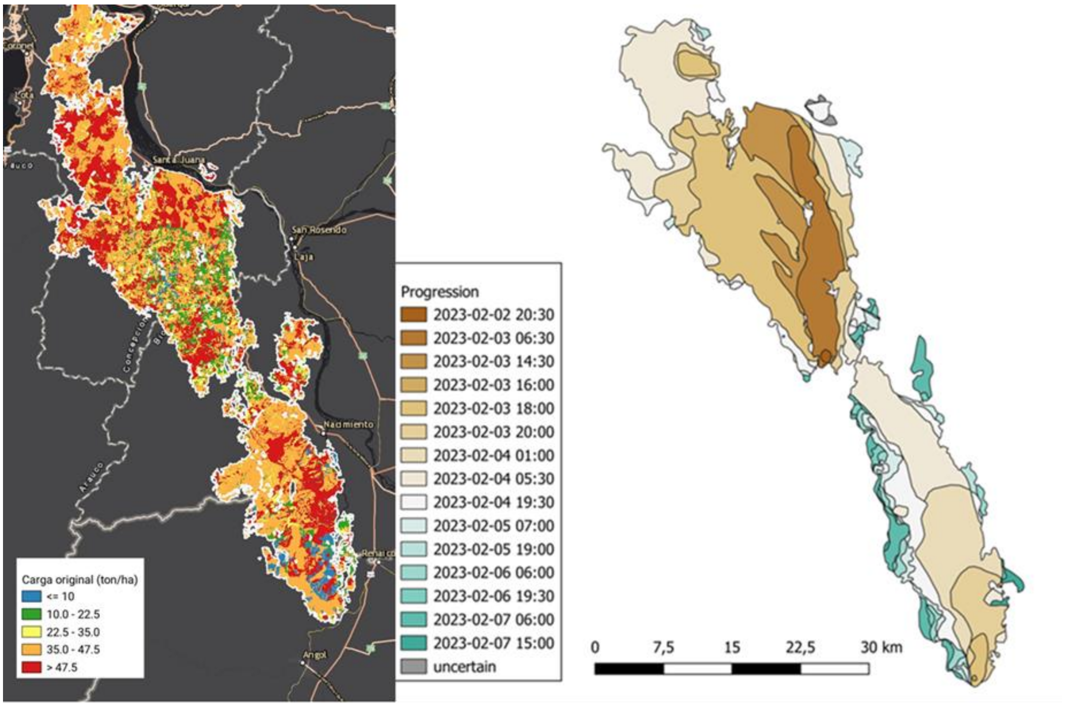
Annex Figure 7. Determination of the height convection column using the GOES 16 satellite and radiosondes of GFS model.

Additionally, the development of a convective column reaching 370 Hpa (8.17 km altitude) was observed, and the energy released by the fire managed to halt the entry of the coastal low and reignite all fires near this complex. The other fires, attracted by the Santa Ana fire, also had high but lower growth rates, around 1,000 hectares per hour (EGIF-CONAF, 2023).



Annex Figure 8. Maximum fire run of the Quillota (ex Butaco 3) wildfire in the El Tambillo sector towards the Santa Ana wildfire on February 03rd between 21:00 and 21:30h.

To assess the potential fire advancement described in the previous paragraphs, a script was built in Google Earth Engine to extract date and time values, FRP (Fire Radiative Power), and coordinates from GOES satellite fire/hotspot data. Using these coverages, data from the pixels contained in the affected area were obtained, with a spatial resolution of 2,000 meters, allowing for data availability in 10-minute intervals.



Annex Figure 9. Fire progression and fuel load maps of Santa Ana and Quillota (ex Butaco 3) Source: CONAF - Development and Research Department; Akli Benali - Forestry Research Center, University of Lisbon.

With these isochrones, it was possible to determine the main fire run, from tail to head, where emergency response interventions are limited, and propagation is more unrestricted. Main runs were determined for each isochrone, and an average propagation speed was calculated for each one. Based on these runs, data on fuel loads present in a 100-meter-wide buffer were collected. Finally, by associating this information with fuel models, the heat content of each fuel type was obtained, and fire intensity according to Byram was determined.

Annex Table 2. Progression of isochrones and fire behaviour based on satellite observations of the Santa Ana and Quillota (ex Butaco 3) fires.

FECHA HORA	FUENTE	INCENDIOS	INTENSIDAD DEL FUEGO (Kw/m)	LONGITUD DE LLAMA (m)	VELOCIDAD DE PROPAGACIÓN (m/min)	TIPO DE FUEGO / CAPACIDAD DE CONTROL
02-02-2023 17:20	GOES16	SANTA ANA INICIO	INICIO ACTIVIDAD SANTA ANA			Incendio altamente turbulento dominado por la columna de convección, propagación caótica e impredecible, focos secundarios a larga distancia / Imposible de controlar
03-02-2023 3:00	LANDSAT, VIIRS	SANTA ANA	38.147	10	45	
03-02-2023 11:30	LANDSAT, GOES16	SANTA ANA	27.310	8	29	Incendio de copa, focos secundarios, propagación caótica e impredecible / Virtualmente imposible de controlar
03-02-2023 13:30	GOES16	BUTACO 3 / QUILLOTA INICIO	INICIO ACTIVIDAD BUTACO 3			
03-02-2023 15:00	SENTINEL2, VIIRS, MODIS	BUTACO 3 / QUILLOTA	40.318	10	52	Incendio altamente turbulento dominado por la columna de convección, propagación caótica e impredecible, focos secundarios a larga distancia / Imposible de controlar
03-02-2023 15:00	SENTINEL2, VIIRS, MODIS	SANTA ANA	POSIBLE FOCO SECUNDARIO SANTA ANA			
03-02-2023 15:00	SENTINEL2, VIIRS, MODIS	SANTA ANA	46.296	11	58	
03-02-2023 17:00	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA	35.117	9	63	
03-02-2023 17:00	SENTINEL2, VIIRS	SANTA ANA	7.529	5	7	Incendio superficial, probable antorcheo / Extremadamente difícil de controlar
03-02-2023 17:00	SENTINEL2, VIIRS	SANTA ANA	43.340	10	40	Incendio altamente turbulento dominado por la columna de convección, propagación caótica e impredecible, focos secundarios a larga distancia / Imposible de controlar
03-02-2023 21:00	SENTINEL2, VIIRS	SANTA ANA	POSIBLE FOCO SECUNDARIO SANTA ANA			
03-02-2023 21:00	SENTINEL2, VIIRS, GOES16	SANTA ANA	53.836	11	52	
03-02-2023 21:00	SENTINEL2, VIIRS, GOES16	BUTACO 3 / QUILLOTA	43.676	10	40	
03-02-2023 23:00	SENTINEL2, VIIRS, GOES16	BUTACO 3 / QUILLOTA (BIOBÍO EX TAMBILLO INICIO)	117.758	16	144	Incendio altamente turbulento dominado por la columna de convección, desarrollo de tormentas de fuego, frente de llama errático debido a la turbulencia y vorticidad, focos secundarios masivos a larga distancia / Imposible de controlar
04-02-2023 16:30	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	3.209	3	4	Fuego de superficie, posible antorcheo / Muy difícil de controlar
04-02-2023 16:30	SENTINEL2, VIIRS	SANTA ANA	1.643	2	2	Fuego de superficie / Moderadamente difícil de controlar
05-02-2023 2:00	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	1.232	2	1	Fuego de superficie / Moderadamente difícil de controlar
05-02-2023 2:00	SENTINEL2, VIIRS	SANTA ANA	1.899	2	3	Fuego de superficie / Moderadamente difícil de controlar
05-02-2023 16:00	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	699	2	1	Fuego de superficie / Moderadamente difícil de controlar
05-02-2023 16:00	SENTINEL2, VIIRS	SANTA ANA	1.487	2	1	Fuego de superficie / Moderadamente difícil de controlar
06-02-2023 3:00	SENTINEL2, VIIRS	SANTA ANA	1.314	2	1	Fuego de superficie / Moderadamente difícil de controlar
06-02-2023 3:00	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	1.314	2	1	Fuego de superficie / Moderadamente difícil de controlar
06-02-2023 16:30	SENTINEL2, VIIRS	SANTA ANA	802	2	1	Fuego de superficie / Moderadamente difícil de controlar
06-02-2023 16:30	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	763	2	1	Fuego de superficie / Moderadamente difícil de controlar
07-02-2023 1:00	SENTINEL2, VIIRS, MODIS	BUTACO 3 / QUILLOTA / EX TAMBILLO	3.152	3	3	Fuego de superficie, posible antorcheo / Muy difícil de controlar
07-02-2023 1:00	SENTINEL2, VIIRS	SANTA ANA	2.364	3	2	Fuego de superficie, posible antorcheo / Muy difícil de controlar
07-02-2023 1:00	SENTINEL2, VIIRS	BUTACO 3 / QUILLOTA / EX TAMBILLO	12.750	6	12	Incendio de copa, focos secundarios, propagación caótica e impredecible / Virtualmente imposible de controlar

Source: Prepared from Tedim et al, 2018.

According to the definitions established by a group of experts within the Horizont2020 FIRE-RES project, in which CONAF participates, the following has been defined:

- Extreme Wildfire Events (EWE) are defined as wildfires with large-scale, complex interactions between fire and the atmosphere, generating pyroconvective behaviour and coupling processes that result in rapid, intense, uncertain, and accelerated fire behaviour.
- They exceed technical control limits (fireline intensity of 10,000 kW/m; propagation speed >50 m/min; passive spotting distance exceeding 1 kilometer; and extreme growth rate values (ha/h).
- The behaviour is unpredictable using operational models, with moments of observed fire behaviour that greatly exceed expectations, surpassing the emergency decision-making capacity.

Annex Table 3. Classification of Extreme Wildfire Events (EWE) based on fire behaviour and control capacity.

	Fire Category	Real Time Measurable Behavior Parameters			Real Time Observable Manifestations of EFB				Type of Fire and Capacity of Control *
		FLI* (kWm^{-1})	ROS (m/min)	FL (m)	PyroCb	Downdrafts	Spotting Activity	Spotting Distance (m)	
Normal Fires	1	<500	<5 [a] <15 [b]	<1.5	Absent	Absent	Absent	0	Surface fire Fairly easy
Normal Fires	2	500–2000	<15 [a] <30 [b]	<2.5	Absent	Absent	Low	<100	Surface fire Moderately difficult
Normal Fires	3	2000–4000	<20 [c] <50 [d]	2.5–3.5	Absent	Absent	High	≥100	Surface fire, torching possible Very difficult
Normal Fires	4	4000–10,000	<50 [c] <100 [d]	3.5–10	Unlikely	In some localized cases	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme Wildfire Events	5	10,000–30,000	<150 [c] <250 [d]	10–50	Possible	Present	Prolific	>1000	Crown fire, either wind- or plume-driven Spotting plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Chaotic and unpredictable fire spread Virtually impossible
Extreme Wildfire Events	6	30,000–100,000	<300	50–100	Probable	Present	Massive Spotting	>2000	Plume-driven, highly turbulent fire Chaotic and unpredictable fire spread Spotting, including long distance, plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Impossible
Extreme Wildfire Events	7	>100,000 (possible)	>300 (possible)	>100 (possible)	Present	Present	Massive Spotting	>5000	Plume-driven, highly turbulent fire Area-wide ignition and firestorm development non-organized flame fronts because of extreme turbulence/vorticity and massive spotting Impossible

Note: [a] Forest and shrubland; [b] grassland; [c] forest; [d] shrubland and grassland; *FLI classes 1–4 follow the classification by Alexander and Lanoville

Source: Tedim et al, 2018.

Therefore, based on the analyses and calculations performed, it is possible to observe and corroborate with field information that from the onset of the Santa Ana fire until February 4, 2023, at 16:30, this wildfire complex was completely beyond suppression capacity, belonging to the Extreme Wildfire Event (EWE) category. It was dominated by a convective column with the release of massive secondary fire spots and erratic flame fronts due to turbulence and vorticity generated by the convergence of strong winds.

For nearly two days, the fires moved within EWE categories 5, 6, and 7 (Tedim et al., 2018), completely beyond prediction capacity. The most critical moment was established between 21:00 and 23:00 on February 3, 2023, with a fireline intensity (FLI) over 110,000 kW/m and a rate of spread (ROS) of over 140 m/min. Within this period, a maximum ROS was reached where 9 km were covered in 30 minutes, as mentioned earlier.

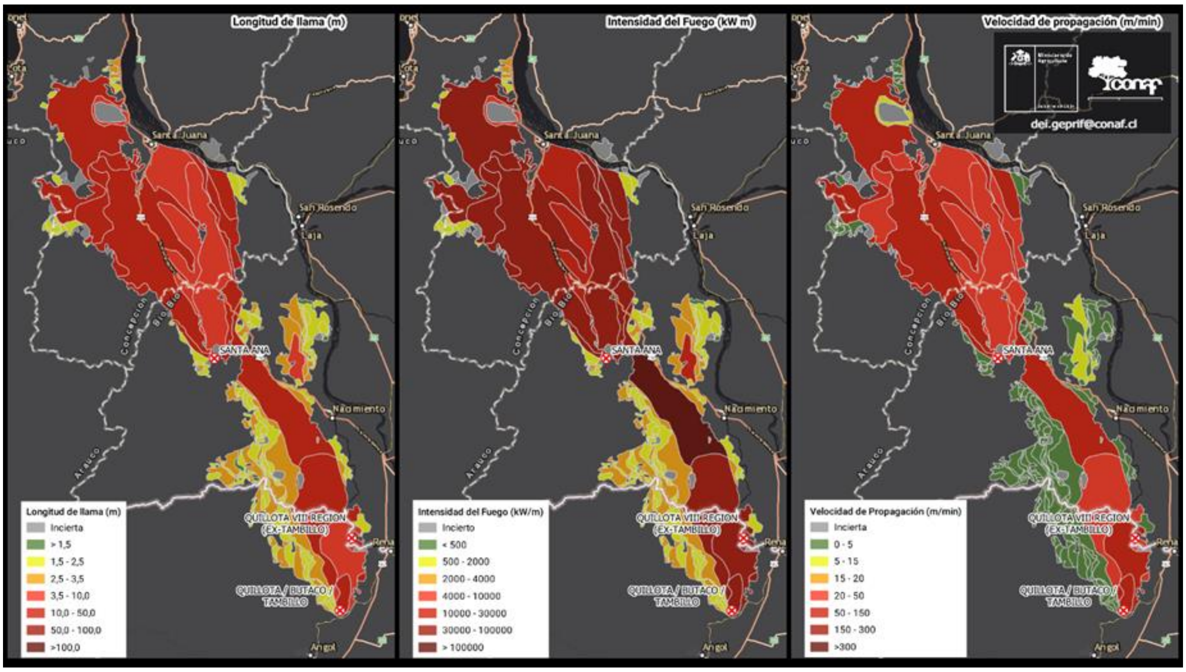
Annex Figure 10. Visual representation of EWE definition.
Source: Adapted from Tedim et al, 2018.

In terms of fire behaviour (Annex Table 2), the EWE that occurred in February 2023 is only comparable to fire behaviours observed during the event in January 2017. Preliminary results from the February 2023 episode show a propagation rate exceeding 7,000 ha/h, advance speeds of 18 km/h, and average front intensity in the main fire run exceeding 100,000 kW/m (Annex Figure 10).

Regarding the extreme event experienced during the summer of 2017, surface propagation speeds of 8,142 ha/h were recorded (observed records for the Las Máquinas Complex) (EUCPT, 2017; EGIF-CONAF, 2023).

Annex Table 4. Summary of fire behaviour in emergencies of 2017 and 2023.

Variables	2017 wildfires	2023 wildfires
Max Rate of Spread (km/h)	> 6	18
Surface ROS (ha/h)	8.142	7.000
Fire Radiative Power (GW)	250 aprox.	95



Annex Figure 11. Fire behaviour parameter maps for Santa Ana and Quillota (ex Butaco 3) fires.

EMERGENCY CHRONOLOGY

Simultaneity and Rate of Progression

Regarding the conditions of simultaneity, which were evaluated based on the territories where daily hotspots were recorded, it was determined that for the period from February 1st to 4th, from Ñuble to La Araucanía, the total affected area encompassed 66 municipalities, with an estimated surface area of 329,280 hectares distributed as follows:

- Ñuble: 86% of municipal impact (18 out of 21 municipalities), covering 69,120 hectares.
- Biobío: 81% of municipal impact (25 out of 31 municipalities), covering 138,880 hectares.
- La Araucanía: 72% of municipal impact (23 out of 32 municipalities), covering 121,280 hectares.

Additionally, throughout the period, 1,029 territorial units or locations (pixels corresponding to 4 km2) were detected with wildfire impact (Figure 13).

Annex Figure 12. Simultaneity of hot spots recorded during the period February 1st - 4th.

The chronology of the event is detailed below with the most relevant episodes (Figure 13).

February 2nd

18:00: The maximum concentration of locations and energy released was recorded in the communes of Coelemu, Ránquil, Quirihue, Chillán Viejo, Lumaco, and Nacimiento. At this time, 31 communes were affected, covering an approximate area of 40,960 hectares.

23:00: A shift in the trend occurred, with the Biobío Region taking the lead in location concentration and energy release statistics. This shift was mainly driven by the activity of the Santa Ana fires in Nacimiento and the El Cortijo fires in Tomé and Florida. At this point, there was a reduction in the affected area and communes compared to the previous period.

February 3rd

During the early hours, there was a noticeable reduction in hotspots and energy release, reaching a turning point for both variables.

14:00: The Quillota fire (ex Butaco 3) started in the commune of Angol, which then progressed northward towards Renaico during the afternoon.

19:00: The Santa Ana fire reached its peak energy release.

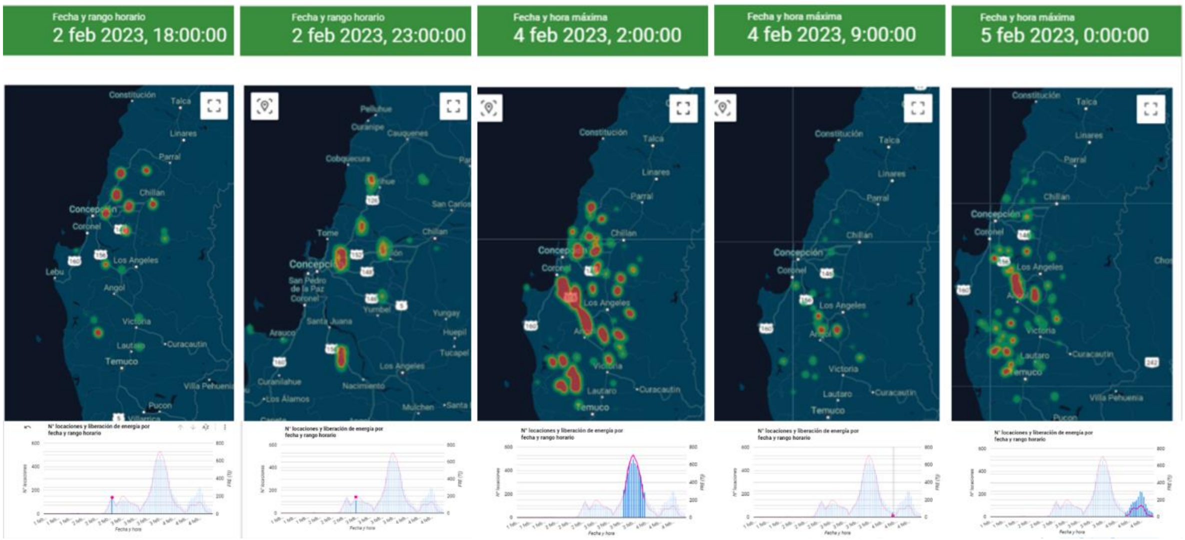
23:00: Over a span of 3 hours, the Quillota fire (ex Butaco 3) continued its advance in a northwesterly direction, crossing the Tambillo area in the Biobío Region.

February 4th

01:00: The Quillota fire (formerly Butaco 3) reached the starting point of the Santa Ana fire.

09:00: There was a significant reduction in hotspots and energy release, reaching the minimum recorded for both parameters.

09:00 and 23:59: An interesting pattern was observed throughout the entire interval; there was a higher number of hotspots compared to the energy released, indicating a larger surface area affected by fires (or more fire spots), but with a lower intensity of energy release. This situation occurred predominantly in the Ñuble Region.



Annex Figure 13. Hotspots between February 2nd and 5th.

Regarding the timing of wildfires and their occurrence throughout the day (Figure 13), for the entire analyzed period, the highest intensity and number of hotspots were concentrated between 18:00 and 20:00, whereas the lowest intensities and number of hotspots were concentrated between 08:00 and 10:00. The occurrence of hotspots during the nighttime period (23:00 to 07:50) is noteworthy. Below are the details of hotspots during the night and early morning of each day.

February 1st

6 hotspots were detected, all in the La Araucanía Region, affecting Victoria, Collipulli, and Traiguén, with a total area of approximately 1,920 hectares. These hotspots did not correspond to significant fires.

February 2nd

Presence of 11 hotspots spread across 3 regions and affecting 4 communes, with the most significant being in the Ñuble Region, in the commune of Chillán Viejo. These hotspots corresponded to the Quilmo and Caserío Linares 2 fires.

February 3rd

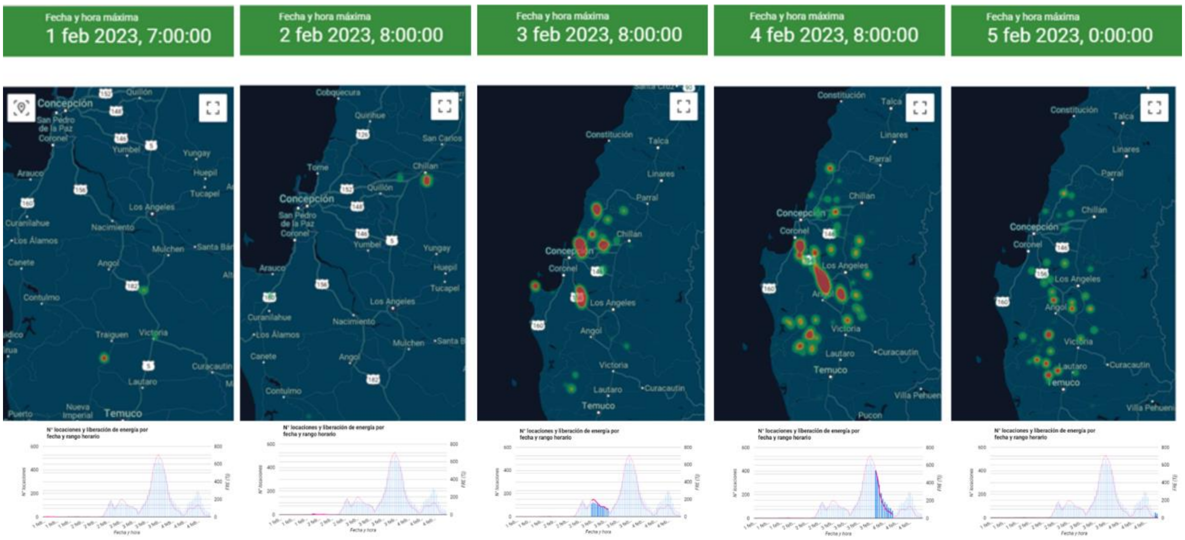
Greater activity was observed compared to the previous night and early morning, with 182 hotspots affecting 26 communes in 3 regions, covering 58,240 hectares. The Biobío and Ñuble regions were the most affected.

February 4th

The highest nocturnal activity of the analyzed period was recorded, with 468 hotspots spread across 47 communes in 3 regions, affecting 149,760 hectares. The Biobío and La Araucanía regions were the most affected.

February 5th

52 hotspots were recorded, spread across 26 communes and affecting 16,640 hectares in 3 regions, with a higher occurrence in the La Araucanía Region.



Annex Figure 14. Seasonality and occurrence of fires.

Reference: *Corporación Nacional Forestal (CONAF). 2023. Informe sobre la emergencia de incendios forestales del 2023. Gerencia de Protección contra Incendios Forestales.*

ANNEX 3. BRIEF REPORT ON RADIOSONDE LAUNCHING TEAM FOR DATA COLLECTION IN CHILE 2023 (CFRS)

Radiosonde launching team for data collection

COMPONENTS OF THE TEAM

The team was made up of the following members of Catalan Fire and Rescue Service (CFRS, Bombers) de la Generalitat de Catalunya:

- Director of the research: Marc Castellnou
- Head of the team in Chile: Jordi Pagès
- Team in Chile: Borja Ruiz and Laia Estivill
- Remote team: Marc Castellnou and Mercedes Bachfischer

OBJECTIVES

The objective of the team was to collect atmospheric data and vertical profiles from outside the smoke plume and especially from inside and on-field. It was also important to collect data of the functioning of the convection columns and fire behaviour within the interaction zone of the forest fires that show convective behaviour with the atmosphere in order to validate the models that Catalan Fire and Rescue Service is implementing in the analysis of forest fires.

These models will increase the knowledge of the forest fire community about the fire-atmosphere coupling processes and will improve the decision making of emergency managers in situations of this type.

An example of how and what these data are used for research purposes and their usefulness in emergency decision-making is described in the research article by Castellnou, M., et al. (2022).

RADIOSONDES LAUNCHING REGION

Wildfires occur in almost all regions of the world, but not all of them have a sufficient capacity for convective development to reach extreme behaviour that is capable of interacting with the atmosphere.

Although extreme or prone behaviour has been seen in various regions of the world, the recognised extreme wildfires that have developed to their maximum potential have occurred in very specific locations [Portugal, Chile and USA (2017); North-EU, South Africa and USA (2018); Bolivia (2019); Australia, Argentina and USA (2020)].

These extreme behaviours are becoming increasingly frequent in different parts of Europe. It is therefore important to observe the phenomenon in those places where it has been occurring for years, in order to understand in which situations these extreme behaviours develop and to be able to anticipate emergency scenarios and improve the speed of decision-making.

DEVELOPMENT

The tasks to be carried out will be as follows:

1. Monitoring of the convective forest fire risk situation to identify those areas with the highest probability of obtaining data.
2. Meteorological prediction of the capacity of the atmosphere to create pyroconvection.
3. Selection of the most optimal locations in the fire environment for the launching of radiosondes and for the collection of control data.
4. Radiosondes launching.
5. Transfer of collected data for remote analysis.
6. Radiosonde recovery process within 0-3 days after the launching.
7. Document the smoke plume type within the fire area using different formats (e.g. video, image, etc.).
8. Document the actions of the team using different formats (e.g. video, image, etc.).

It is important to note that on that occasion once the data had been collected, although some of the data was possible to be viewed using the software installed on a laptop PC, there was not a detailed on-time analysis to be used on the spot for operational decision making.

Software used in the field on a handheld device allowed data to be viewed in a format that was not useful for reading. These data needed to be processed through code that allowed them to be reflected in a Skew-T (temperature slope) log-p (pressure or logarithmic height) plot. These graphs alone do not allow the detection of extreme behaviour as it is a real time reading at the moment the data is observed and not a prediction.

In other words, the whole process is still in the research and data accumulation phase (in this case in the Southern Hemisphere). In the future, with more data and when the appropriate models have been improved, it will be possible to have a first analysis in a short time to facilitate decision-making in emergency management.

METHODOLOGY

Thirty Windson radiosondes model S1H3-R (http://windsond.com/) were used to cover as many events as possible within the period between the 1st and 28th of February of 2023 during the Chilean forest fire campaign. The radiosondes launch methodology used in Castellnou, M., et al. (2022) described schematically in the following scheme was followed:

Specifications S1H3	
Operating range	-40 ~ +80° C 0 ~100% RH
Temperature sensor	Type: Band gap Accuracy: 0.3 °C Resolution: 0.01 °C
Humidity sensors	Type: Capacitive Accuracy: 2.0 %RH Resolution: 0.05 %RH
Air pressure	Range: 300 – 1100 hPa Resolution: 0.02 hPa Accuracy: 1.0 hPa (at 700 – 1100 hPa)
Wind direction	Resolution: 0.1°
Wind speed	Range: 0 – 150 m/s
Sonde weight	12 gram
Max altitude	9000 m MSL

Fig. 1. Windsond Technical Specifications. For full specifications see the complete product catalogue. (http://windsond.com/windsond_catalog_Feb2019.pdf).

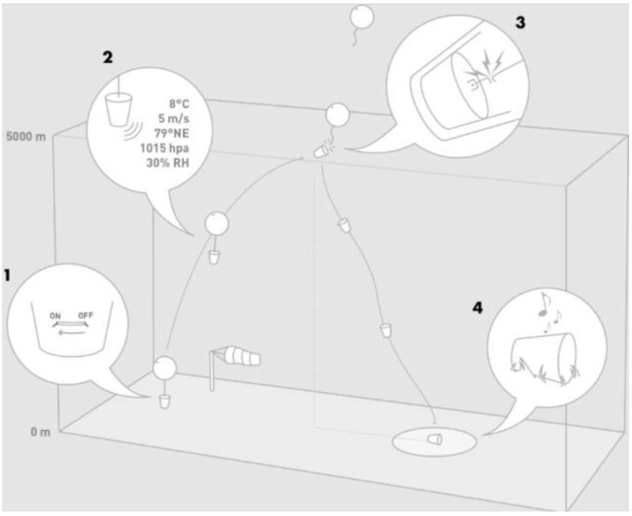


Fig. 2. Overview of how Windsond works (http://windsond.com/)

INTEGRATION IN THE EGIF TEAM

Equipo de Gestión de Incendios Forestales (EGIF) was a programme for the exchange of knowledge and working methodologies at international level sponsored by the Corporación Nacional Forestal de Chile (CONAF) and carried out by the Pau Costa Foundation (PCF) during the 2022 and 2023 fire campaigns.

The 2023 edition involved members of the following organisations: Bombers de la Generalitat de Catalunya, Equipo Técnico de Acción ante Catástrofes (ETAC), Forest Fires Assessment and Advisory Team (FAST), Força Especial de Proteçáo Civil (ANEPC-Portugal), Incendios forestales de Castilla - La Mancha (INFOCAM), Lefthand Fire Protection District, Servicio Operativo de Extinción de Incendios Forestales de Andalucía (INFOCA), Unidad de Defensa Contra Incendios Forestales de Murcia (UDIF), UT 902 VAERSA Grupo - Generalitat Valenciana.

The Catalan Fire and Rescue Service (CFRS, Bombers) radiosondes launching and data collection team was part of the Forest Fire Analysis and Research Cell (Heads: Jordi Pagès and Jordi García) of the EGIF. This cell has the following functions (in bold, the areas where the radiosonde team was integrated):

1. Exchange of working methodologies to predict fire behaviour and establish work priorities based on what the fire wants to do and is able to do.
2. Providing support to the National Forest Fire Coordination Centre (CENCOR) and the Advanced Command Post (PUMA) on the fire situation.
3. Design of fire analysis reports.
4. Assistance in the implementation of the logical methodology of the decision-making process in forest fires, in accordance with the AFAN Guidelines. Analysis-Operations Architecture
5. Development of ArcGis online project for information collection and transfer. Forest fire database.
6. Research on observed fire behaviour and vertical state of the atmosphere.

The team was composed of three work areas:

a) Strategic Analysis Area
b) Tactical Analysis Area
c) Research and GIS Area

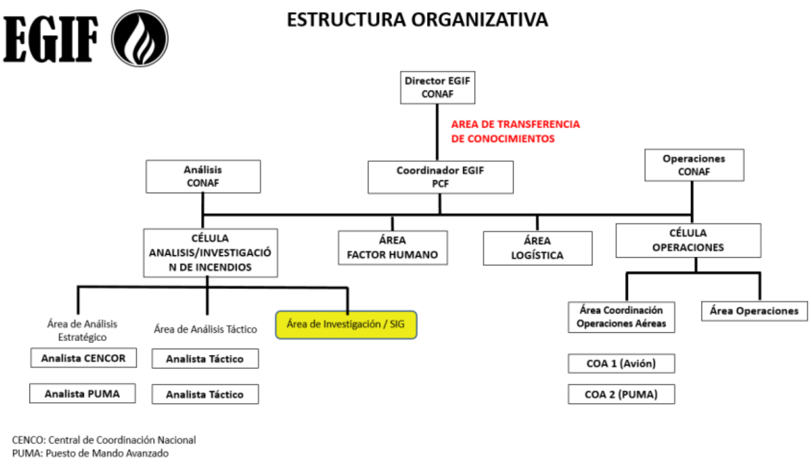


Fig. 3. Location of the radiosonde team for data collection within the EGIF organisational structure.

FIRE-RES PROJECT

FIRE-RES is a 4-year project (2021-2025) led by the Centre of Forest Science and Technology of Catalonia in Spain and funded under the European Union's H2020 research and innovation programme (https://fire-res.eu/about-fire-res/).

FIRE-RES aims to develop a comprehensive and integrated fire management strategy to efficiently and effectively address extreme forest fire events in Europe by developing concrete innovation actions.

Within the FIRE-RES project, Catalan Fire and Rescue Service (CFRS, Bombers) leads the operational part of the fire and landscape management strategy, technological development and emergency communication. To this end, it leads the working group focused on the harmonisation of knowledge on forest fire analysis, the identification of tools and best practices in this field and on remote analysis of forest fires, with the aim of establishing a common framework for forest fire analysis at European level.

CFRS also carries out a number of specific Innovation Actions. One of these actions consists of determining and testing the key inputs for the analysis of atmospheric data that have an influence on the generation of extreme forest fires and to do so using new knowledge and experience about them.

GLOSSARY

Extreme Wildfire Events (EWE): Extreme Wildfire Events (EWE) are defined as wildfires with complex large-scale fire-atmosphere interactions that generate pyroconvective behaviour, coupling processes, resulting in changing, intense, uncertain and fast-paced fire behaviour. Furthermore, it results in fire behaviour that exceeds the technical limits of control (flame front intensity 10,000 kW/m; spread speed > 50 m/min; secondary fire distance > 1 km, massive secondary fire launch and extreme growth rate (area per hour, ha/h). At the same time, this extreme outbreak behaviour is unpredictable using current operational models, with observed outbreak behavioural moments much higher than expected. This overwhelms the decision-making capacity of the emergency system (bomber teams and emergency managers, infrastructure managers and civilian population). It may pose a greater threat to firefighters, the population,and natural values, and may cause relevant negative socio-economic and environmental impacts (definition D1.1 FIRE-RES).

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www.windsond.com
www.sparvembedded.com
www.fire-res.eu

ANNEX 4. DEFINITIONS

These definitions are not derived from any consensus or specific reference. They are included in this document only to clarify the explanation of the parameters listed in Table 1.

Heat **Fluxes (HF) between surface and atmosphere**: the release of energy between the surface where the EWE is located and the atmosphere.

Entrainment and detrainment: Entrainment is a one-way transport process from the ambient fluid to the flowing turbulent fluid of a jet, in the case of fires, of the air moving up in the fire smoke plume. Detrainment is the opposite transport of air in a convective cloud or convective fire from the cloud or fire to the environment.

In-draft speed of the smoke plume: speed from the entrance of air into the smoke column.

Fire-atmosphere coupling triggers: elements that are key to boost the process of the fire-atmosphere coupling during an EWE.

Atmospheric vertical profile from inside the fire smoke plume: weather and fire conditions (temperature, humidity, pressure, etc.) from the vertical axis where the fire is located.

Flammability of the landscape: contribution of the fuel to the ignition due to dryness, moisture or typology and to the maintenance of the combustion on it has initiated.

Moisture outside the fire: humidity taken from outside the fire column, at certain distance, but which may contribute to a change in behaviour due to its entry into the fire.

FIRE-RES