Overview

This preprint presents a novel and practical methodology for characterizing pyroconvective wildfire plume dynamics using dual radiosonde soundings (in-plume and ambient). The study spans 156 field launches across four countries between 2021 and 2025 and offers both operational and scientific insights into plume development, real-time hazard awareness, and fire-atmosphere interaction modelling.

The manuscript is timely, rigorously detailed, and bridges a rare and valuable gap between operational field constraints and mesoscale meteorology. The work is distinguished by its applied innovation, extensive empirical validation, and potential to substantially inform firefighter safety procedures.

Strengths

1. Novel Methodology with Operational Value

- The use of paired in-plume and ambient radiosonde profiles is both innovative and cost-effective, rendering it feasible for deployment during active wildfires.
- The operational integration into tactical decision-making workflows sets this study apart from traditional simulation-based or laboratory-bound research on pyroconvection.

2. Robust Field Campaign

- With 156 launches covering a diverse range of vegetation types, meteorological conditions, and terrain profiles, the dataset represents an impressive empirical foundation.
- The inclusion of both prescribed burns and uncontrolled wildfires increases the method's general applicability.

3. Validation Through Multi-Modal Comparison

- Plume-top altitudes inferred from vertical velocity profiles were validated against radar echotop data, which significantly strengthens confidence in the method.
- Application of parcel theory for forecasting potential plume development (e.g., pyroCu onset) is methodologically sound and well-executed.

4. Classification Framework

- The six-category plume prototype typology (based on ABL height, LCL height, and wind shear layers) is operationally intuitive and scientifically coherent.

5. Actionable Outcomes

- Several case studies (e.g., Martorell and Santa Ana) demonstrate that tactical decisions informed by the sonde data likely contributed to risk mitigation. This real-world applicability is a major strength.

We thank the reviewer for the summary and very positive assessment of our work, and specifically the recognition of our methodology and data set.

Weaknesses / Areas for Improvement

1. Clarification of Balloon Typology (Ref. Line 145, Table 1)

- The classification "professional high-altitude balloon" is misleading. A more accurate term would be **"operational radiosonde systems"**, as both small and large balloons may be used professionally. For instance, an MW51 Vaisala ground station combined with an RS41 sonde and a Totex TA50 or TA100 balloon could easily reach 400 hPa level, albeit with higher helium demand.

  Thank you for your input. We aim to clarify the misleading terms by using the proposed "operational radiosonde systems." In Table 1, instead of 'Professional high-altitude balloons'

  Although we are aware of the various types of radiosondes that are referred to by the reviewer, our reasons for designing and developing the light system are related to the safety requirements set by the aerial controller of the fire.

  In line 136, where it said: 'Safe for operating along with aerial resources'

  We will add the next new text:

  "Ensure compliance with specific safety requirements that may differ from general aerial control regulations. These are proposed by the fire service aerial coordination for operating alongside firefighting aerial resources: radiosondes weighing less than 50 grams and colored balloons with a capacity of less than 90 liters. Note that these requirements may vary internationally, and we adhere to the strictest standards."

- Table 1 also incorrectly claims that such systems are incapable of simultaneous launches. In fact, MW51 systems can track up to four sondes concurrently and have portable variants.

  We will adapt the table accordingly.

- Furthermore, the claim that professional radio-sounding systems are "not safe for aerial resources" is inaccurate. All operational weather balloons (regardless of size) comply with aviation safety regulations. In contrast, marking helicopters as inherently "safe" for aerial operations is misleading, as such platforms require **strict coordination with air traffic control and firefighting aviation assets**. These inaccuracies should be revised to reflect standard aviation safety protocols.

  The aerial control during a wildfire establishes the specific requirements for the simultaneous operation of drones and radiosondes alongside helicopters and planes. As stated in the previous clarification in the first paragraph of this section, the radiosonde system must meet the safety requirements specified by the aerial coordination within the fire service *team. This adaptation involves using the lightest possible radiosondes and colored balloons to ensure visibility.*

2. Reliability of Windsonde Data During Descent (Ref. Line 190)

- The authors should clearly state that **measurements during descent are generally considered less reliable**, even for professional sondes. Windsonde systems have not been formally validated for descent-phase data collection.

In the new modified text, we acknowledge that such measurements are less reliable and can exhibit discrepancies of tens of meters. However, in our study, we have achieved a satisfactory accuracy within the profiling. This has allowed us to propose and apply a classification of pyroconvection prototypes (Castellnou et al., 2022), which is the primary goal of the proposed methodology. Although less reliable, profile measurements taken during descent still enable us to identify key metrics in the fire-weather interaction, such as the ABL and LCL heights (with 82 m uncertainties in their height estimations).

Please note that our methodology includes launching separate radiosonde not influenced by the fire conditions to obtain complete and more comprehensive observational evidence of the interaction between the plume and the surrounding environment. However, if due to whatever circumstances this is not successful or possible, we can use the measurements taken during a sonde's descent (attempting to endure those outside the plume) as a best approximation. Such measurements are a much better estimation than ambient radiosondes from 10s to 100s of km and hours of difference, as normally used as reference in pyroCu studies (Lareau and Clements, 2016; Tory et al., 2018)

We provide additional complementary materials, statistically comparing the profiles of ascent and descent of the same sonde in Figure 5 as detailed below.

Accordingly, we change the text in line 190:

<u>Old version:</u>

'Ambient sonde:

Launched outside the fire influence (Figure 2), it measures the vertical profile of the state variables in an environment uninfluenced by the fire plume.

Although launching a separate ambient sonde is recommended, our campaign findings indicate that an ambient profile can also be obtained from the in-plume sonde descent path if the sonde is cut-down once it is outside the plume's influence. By comparing data from both the in-plume descent and the ambient sondes, we can improve the reliability of our findings.'

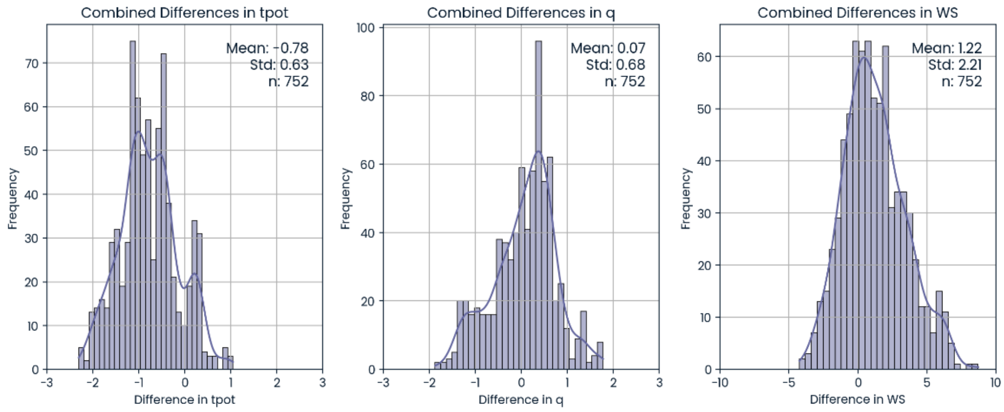
<u>New version:</u>

'Ambient sonde:

Launched outside the fire influence (Figure 2), it measures the vertical profile of the state variables in an environment uninfluenced by the fire plume. By comparing data from both the in-plume descent and the ambient sondes, we can improve the reliability of our findings.

Although launching a separate ambient sonde is recommended, our campaign findings suggest that it may sometimes be operationally impractical. However, an ambient profile can also be obtained from the in-plume sonde descent path if the sonde is cut-down once it is outside the plume's influence. Although less reliable (mean absolute error: 82 m), analysis of such profiles measurements taken during descent still enables us to identify key metrics in the fire-weather interaction, with acceptable variable uncertainty (Figure S5)

Proposed Figure S5:



variable	*Mean of differences*	*Std deviation of differences*
Θ (K)	*0.78*	*0.63*
RH (%)	*2.22*	*6.35*
q (g·kg-1)	*0.07*	*0.68*
WS (m·s-1)	*1.22*	*2.21*

Figure S5: Validation of descending ambient sonde profiles. Evaluation of the mean and the standard deviation between appropriate (ascending) ambient sondes and descending ambient sondes collected during the same fires. The results indicate that the measurements are acceptable for the assessment of pyroconvection prototypes. Such profiles are essential when ambient sonde data for comparison with in-plume profiles is unavailable. In these instances, in-plume sondes descending outside the fire area can supply needed ambient data.

- As shown in Bessardon et al. (2016, Kumasi campaign), **ground-based reference measurements** of pressure and temperature were used to calibrate Windsonde outputs. It is unclear whether a similar calibration procedure was applied in this study.

The use of Windsonde was tested and calibrated against Vaisala RS41 sonde used by MeteoFrance team during the 2021 LIAISE campaign (Boone, 2019) of ABL measurements in Lleida (Spain). The windsonde system was adjusted in the field and the measurements showed reliable results. (Castellnou et al., 2022)

- Moreover, the same research highlights concerns regarding **wind speed and direction accuracy**, particularly during turbulent or shear-laden environments. The authors should explicitly discuss whether and how these limitations were addressed.

We acknowledge in the text that turbulence in fire-weather conditions can lead to noisy soundings. Bessardon et al. (2016) highlighted this issue, particularly with irregular patterns in measured horizontal wind speed. They recommend using smoothed lines for analyzing wind speed and direction, as we apply in our analysis. These two parameters are relevant but not crucial for identifying pyroconvective prototypes and have not hindered the analysis of Windsond data during wildfires.

- Known **instrumental limitations** of Windsonde include weak response to rapid humidity and temperature changes, and **systematic underestimation of altitude (up to ~40 m)**. These should be acknowledged and addressed to justify continued use of this platform.

The instrumental limitations for rapid humidity and temperature changes, as well as understimations of altitude, have been well-tested and identified during the LIAISE campaign and in the 2021 fire when comparing radiosonde agreement.

The systematic underestimation of 40 m is not significant for the operational use in identifying the pyroconvection prototypes.

The weaker response to rapidly changing temperature and/or specific humidity with Windsond is not significant for operational use of the sonde (Figure S5), which show well-defined in-plume and outside-plume data.

While the Windsond is known to exhibit a slower response when moving from a cloud to a warmer, drier environment (Bessardon et al., 2019), our study found that the height of this transition effectively serves our purpose. Furthermore, pyrocloud tops identified by radiosonde measurements aligned well with radar data (Figure 8) with a mean absolute error (MAE) of 166,7 m, validating the Windsond's capacity to provide the operational information we need.

Following the discussion in the last three bullets in this section, we will update the original text between lines 153 and 156:

<u>Old version:</u>

'The system has been previously tested against larger, professional radiosondes and successfully achieved relevant measurements, despite its

weaknesses in GPS processing and humidity response time at cloud tops (Bessardon et al., 2019). Previous research that we conducted during active wildfire events demonstrated that these challenges did not hinder the detection of pyroconvective phenomena (Castellnou et al., 2022).'

New version:

'The instrumental capabilities of the system have been previously tested against larger radiosonde systems, as RS41, during the LIAISE campaign (Boone et al, 2019) of ABL measurements in Lleida (Spain). Results showed a strong profile agreement between both radiosondes systems (Castellnou et al. 2022). While certain weaknesses, such as a 40-meter altitude underestimation, issues with GPS processing, slow humidity response at cloud tops, and noisy wind profiles in turbulent conditions (Bessardon et al., 2019), were noted in the plume turbulent conditions, they were not detrimental to the accuracy of identifying pyroconvective prototypes during wildfires (Castellnou et al., 2022).

To continuously validate the Windsond operational effectiveness, we systematically record plume measurements using fire service planes and radars whenever possible

3. Quantitative Predictive Success Rate

The manuscript would benefit from a summary table or appendix quantifying:

- How many launches successfully entered the plume core?
- How many failed or produced partial profiles?
- In what proportion of cases did fire development escalate to **Extreme Wildfire Events (EWEs)**?
- In how many instances did the radiosonde data lead to a tactical change (e.g., crew withdrawal)?

Due to the length of the table with 156 sondes, we will add to the dataset repository of the paper a detailed table for the sondes launched using the next headings:

***Fire:** name of the fire and type: WF (wildfire), PF (prescribed fire). If the wildfire incorporates the (EWE) means it evolved to an extreme wildfire (EWE) of category IV or higher (Tedim et al., 2018)*

***Lat & Long:** latitude and longitude coordinates*

***Data and hour**: identifies launching day and hour*

***Sonde type:** identifies in-plume sondes types (rear-indraft, flank indraft and head indraft), ambient sondes and umbrella sondes as described in Figure 2. Due to this specification, Figure 2 and its description is modified to include the umbrella sondes.*

Success:

S: success, sonde entered the plume.

N: NO success, sonde didn't when into the plume. If sonde failed reason is provided.

Motivation to launch: *goal of the launching*

Impact on decision: *use of the information provided by the sonde. We classify it as:*

Awareness, -sonde provides awareness of the real ambient conditions on-site and real plume deepening into the ABL or FT.

Tactical, sonde information forces tactical adjustment in operations to avoid the impact of potential pyroconvection changes in fire behavior.

Safety, when sonde is used to confirm ongoing pyroconvection transition

Example of the proposed table (the table in the repository totals 166 sondes):

fire	**Date and hour**	**Lat & long**	**Sonde type**	**Success**	**Motivation to launch**	**Impact on decision** **Reason to failure**
WF (EWE) Martorell (CAT)	13/07/2021 16:09:22	41.465158 1.936343	In-plume Rear indraft	S	Validate pyroCu deepening	Tactical
WF (EWE) Martorell (CAT)	13/07/2021 16:25:11	41.453402 1.943707	Ambient	S		
WF (EWE) Martorell (CAT)	13/07/2021 17:05:07	41.467680 1.921600	In-plume Head indraft	S	Validate potential transition to pyroCu	Tactical Safety
WF Torroella de Montgrí (CAT)	22/07/2021 18:42:03	42.071343 3.145890	In-plume Head indraft	S	Validate potential transition to pyroCu	Awareness
WF (EWE) Sta Coloma de Queralt (CAT)	24/07/2021 19:17:38	41.529135 1.383498	Ambient	S		
WF (EWE) Sta Coloma de Queralt (CAT)	24/07/2021 19:41:55	41.528420 1.453758	In-plume Flank indraft	S	Validate potential transition to pyroCu	Awareness
WF (EWE)	25/07/2021 10:40:47	41.510465 1.486245	In-plume Rear indraft	S	Validate potential transition to pyroCu	Tactical

Sta Coloma de Queralt (CAT)						
WF (EWE) Sta Coloma de Queralt (CAT)	25/07/2021 18:19:59	41.517753 1.494428	In-plume Rear indraft	S	Validate pyroCb transition and strenght	Safety
WF La Pobla de Massaluca (CAT)	12/08/2021 15:10:09	41.224933 0.332295	In-plume head indraft	N	Validate pyroconvection prototype	Awareness Launch into a weak-intermitent indraft

A summary table with statistics about success and use will be added in the results section 3.4. Such section is changed accordingly to 'Usability of plume profiling methodology':

Old text:

'3.4 Failed profiles

It is important to note that during the campaigns, we did not observe detrained sondes from the plume once the sonde entered the plume neck. However, we have had cases of sondes failing to enter the plume or entering the plume at higher altitudes when we launch into weak or intermittent indraft conditions. Those cases have always been reported with launching conditions too far away from the head fire (Figure S4) or when we launch into a decaying head fire, and there are strong surface winds present (>6 m·s-1). '

New text:

'3.4 Usability of plume profiling methodology

Over the four years of fire campaigns during which we tested our methodology, we obtained clear results supporting the use of paired ambient-in-plume profiling with radiosondes on active wildfires (see Table 4). The low failure rate of 7.73% and the consistent application of sonde information for awareness and safety indicate that this methodology is well-suited for adapting operational tactics—utilized in 39.7% of our case studies—to address the challenges posed by pyroconvection transitions.

It's important to note that during the campaigns, sondes that failed to enter the plume did so due to being launched too far from the plume base into weak or intermittent indrafts (Figure S4.) and normally in the head or flank indraft. Rear indraft sondes, that better capture the main indraft into the plume can endure longer distances.

Table 4.- Summary of success and use in decision making of the sondes launched (to be completed).

Type of sonde	Proportion over total sondes	description	
Failed sondes	7.73%	61.3% too weak indraft, or launching too far away	
		23% pushed to the ground by rear indraft	
		15.3% due to sonde failure	
operational	73.27%	Awareness	34.1%
		Tactical	32.7%
		Safety	7%
Research	19%		

4. Reproducibility: Launch Schedule and Decision Criteria

- For reproducibility and model intercomparison, the authors should provide a **complete launch schedule overview**, including exact timestamps and GPS coordinates of each sonde release.
- Additionally, the **criteria used to determine the moment and location of launch** should be explicitly stated (e.g., wind indicators, visual cues, forecast thresholds).
- These criteria appear to be field-operational in nature, but formalising them would help transfer the method to other contexts.

The launch schedule data is presented in the table mentioned in point 3. The criteria for launching the sondes, outlined in the 'motivation to launch' field of the table, are based on the operational need to validate the pyroconvection prototype's potential and the likelihood of transitions.

5. Real-Time Workflow and Decision Chain

The article does not describe the **complete operational workflow** from launch to decision. Clarifying the following would significantly improve transparency:

- How is data transmitted to and from the operations centre?
- Who is expected to perform the data analysis (on-site, centralised, or remote team)?
- What additional data sources are used (e.g., satellite, radar, fireline reports)?
- What is the **end-to-end latency** between launch and actionable tactical insight?
- Are any **supporting information systems or software platforms** (e.g., for visualisation or alerting) required or recommended?

In the methodology section, we have added the following information:

'The sonde operational workflow includes the fire analyst being part of the launch team, allowing immediate analysis of observational data collected during the sounding. If the analyst is not present, data is uploaded to cloud storage from field mobile devices for command post analysis. The analyst reviews the vertical profiles to approve or adjust ongoing operations in collaboration with the incident commander and safety officer. Additional

information is gathered from fireline crews, drones, planes, and meteorological radars, when available. Data management should occur within one hour of the in-plume launch, with a two-hour reference limit. The process involves data transfer, visualization software for profiles, and cloud archiving to make the observations accessible to the incident management team.'

6. Sonde Sampling Bias

- The authors acknowledge that sondes may not always enter the plume core, which may skew thermal and vertical velocity readings. Further statistical quantification of this sampling uncertainty would be beneficial.

We acknowledge in the discussion that sondes may not always enter the cores of the plumes. As a result, the readings obtained may underestimate the thermodynamic and vertical velocity characteristics of the more buoyant core inside the fire plume. However, the vertical velocity profile still accurately indicates the plume top height, with discrepancies of only a few hundred meters, which falls within the typical variability of plume tops.

In the manuscript, we detail the launch procedure for accurately measuring the fire plume. As discussed in the modified results section 3.4, the key to success is ensuring the sonde penetrates a well-established plume indraft. This typically requires proximity to the plume (see the added sondes table in the dataset for failure reasons).

It is important to notice that the indraft requirement can't be defined numerically and launching can only proceed when the indraft is physically experienced in the launching site. Sondes launched during the Guisona wildfire on July 1, 2025 into a strong 18 m·s-1 indraft wind, faced significant horizontal trajectories of 9 kilometers within the indraft before entering a plume that was measured having a top at approximately 11200 m AGL by radar. Conversely, sondes released outside or in intermittent indraft from plumes with shallow plume tops (1,000-2,000 m) often failed to reach the plume, needing launching position closer to the plume neck (up to 300 m) to succeed.

This information is added to section 3.4 and the modified complementary figure S4

7. Terminology

- Some terminology (e.g., "θv spike", "fireABL", "S parcel") may not be immediately clear to the broader meteorological or fire-behaviour audience. A glossary or summary table of variables and acronyms is recommended.

Thanks for the observation. We will complement Table 2 and include descriptions so it becomes a complete table of variables and observations describing terms and providing symbols and units to facilitate the reading

	Variable	Description	Units	Source
Readings	sonde ascending profile	Track of the radiosonde path horizontally and vertically.	UTM, m AGL	Profile observation
	Tª (Ts, Td)	Absolute temperature	K	Profile observation
	RH	Relative humidity	%	Profile observation
	P	Pressure	hPa	Profile observation
	U	wind speed	$m \cdot s^{-1}$	Profile observation
	U: w component		$m \cdot s^{-1}$	Profile observation
Variables (S3)	U: u component		$m \cdot s^{-1}$	Computed from profile observation
	U: v component	Vertical wind speed	$m \cdot s^{-1}$	Computed from profile observation
	q	specific humidity	$g \cdot kg^{-1}$	Computed from profile observation
	Θ	potential temperature	K	Computed from profile observation
	$Θ_v$	Virtual potential temperature		Computed from profile observation
Fire-atmosphere interaction (S3 for alternative equations)	Measured plume height		m	Visually displayed on the profile: rise-speed sonde profile stability
	Measured plume height		m	Radar echotop filtered at 12dBZ
	Potential plume height	Plume height estimated by the different parcel methods	m	Parcel method (see parcels type below)
	LCL	Lifting Condensation Level, Height at which a parcel of moist air lifted dry-adiabatically would become saturated	m	Visually displayed on the Skew-T
	ABL	Atmospheric Boundary Layer	m	Visually displayed on the profile: Maximum RH on the ambient sonde profile
	fireABL	fire induced ABL. Modified mixing layer by plume turbulence mixing in the plume area and below the plume umbrella	m	Visually displayed on the profile: Maximum RH value on the in-plume sonde profile
	Wind shear	Wind direction and wind speed vertical gradient	s^{-1}	Visually displayed on the wind speed profile
	CAPE / CIN	convective available potential energy / Convective inhibition	$J \cdot kg^{-1}$	Visually displayed on the Skew-T diagram
Parcels	S	surface parcel	K	Ts at the surface
	ML	mixing layer parcel	K	Ts averaged at lower 150 hPa
	MU	most unstable parcel	K	Maximum Ts at lower 150 hPa
	FRP	fire radiative power	TJ	Obtained from geostationary satellites
	FLI	Expresses the energy the fire is releasing per unit of the forward spreading front	$kW \cdot m^{-1}$	Obtained from measurements by the fire service

Fire	Heat per unit area	Expresses the energy the fire is releasing per unit of surface in the flaming front	$kW\cdot m^{-2}$	Obtained from measurements by the fire service
	hourly isochrones	Hourly perimeter increment by the observed fire spread	ha	Obtained from measurements by the fire service
	Fuel type	Types of vegetation spreading the fire	Fuel model	Scott&Burgan general models: GR (grass), SH (shrub), TU (shrub under trees), TL (litter under tree)
	ROS	Fire front rate of spread	$m\cdot s^{-1}$	Obtained from measurements by the fire service
	Altitude	Fire front altitude above sea level	m ASL	Sonde launching points
	Coordinates	Fire front location	UTM	Sonde launching points
Plume	indraft	radial surface wind at smoke plume base induced by an updraft	$m\cdot s^{-1}$	Profile observation
	updraft	rising convective wind inside a smoke plume. it is the in-plume w component	$m\cdot s^{-1}$	Profile observation
	umbrella	the thick smoke layer downwind from head fire also called pyrostrato.	m AGL	Profile observation
	overshooting	the dry turbulence rising above the average plume top and umbrella.	m	Profile observation
	pyroCu	Cloud formed by a rising thermal from a fire when it reaches LCL (American Meteorological Society, 2021).		See table 3
	pyroCb	Egooxtreme manifestation of a pyroCu when deepening above LCL and rising to the upper troposphere or lower stratosphere (American Meteorological Society, 2021).		See table 3

Suggested Revisions

- Replace ambiguous or inaccurate entries in **Table 1**, particularly regarding balloon classifications, safety, and simultaneous sounding capability.

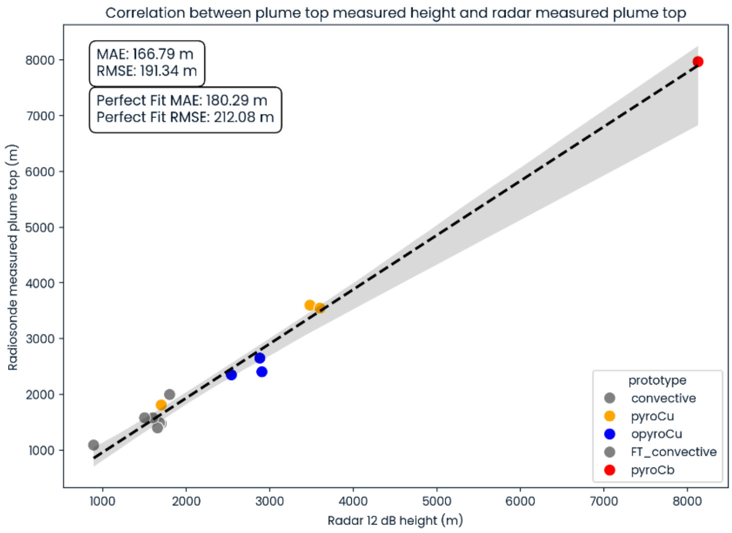
  Done in point 1

- Add a **summary table** of all launches with fire name, time, coordinates, outcome, and tactical decision if applicable.

  Done in point 3

- Include **error metrics** for vertical velocity-derived plume tops compared to radar.

  We provide the data in the new updated Figure 8:



- Clarify how and when real-time analysis was conducted, by whom, and how long it took.

  See Table in point 3

- Address the known **technical limitations** of Windsondes and justify their use despite weaknesses.

  Done in point 2

- Provide access to a **full launch log and reproducibility protocol**, including selection criteria for launch timing and location.

  Done in table in point 3

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