Airborne Observation from Experimental Burn: Fire Behavior Computation, Plume Simulation, and IR image simulation

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UPV Valencia - 22 May 2024

MARIE CURIE ACTIONS

European Commission

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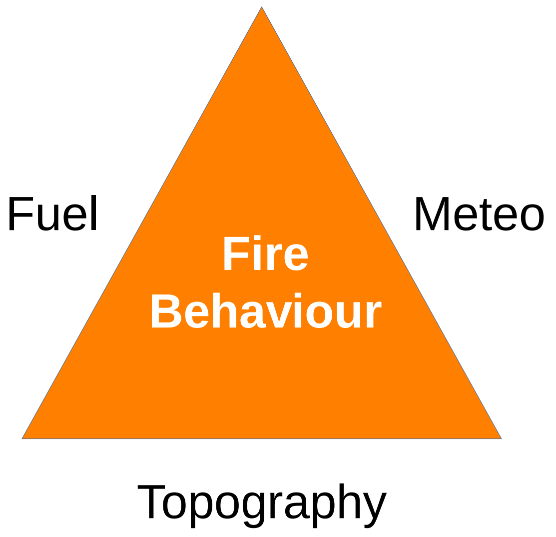
MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

CESBIO

Introduction:



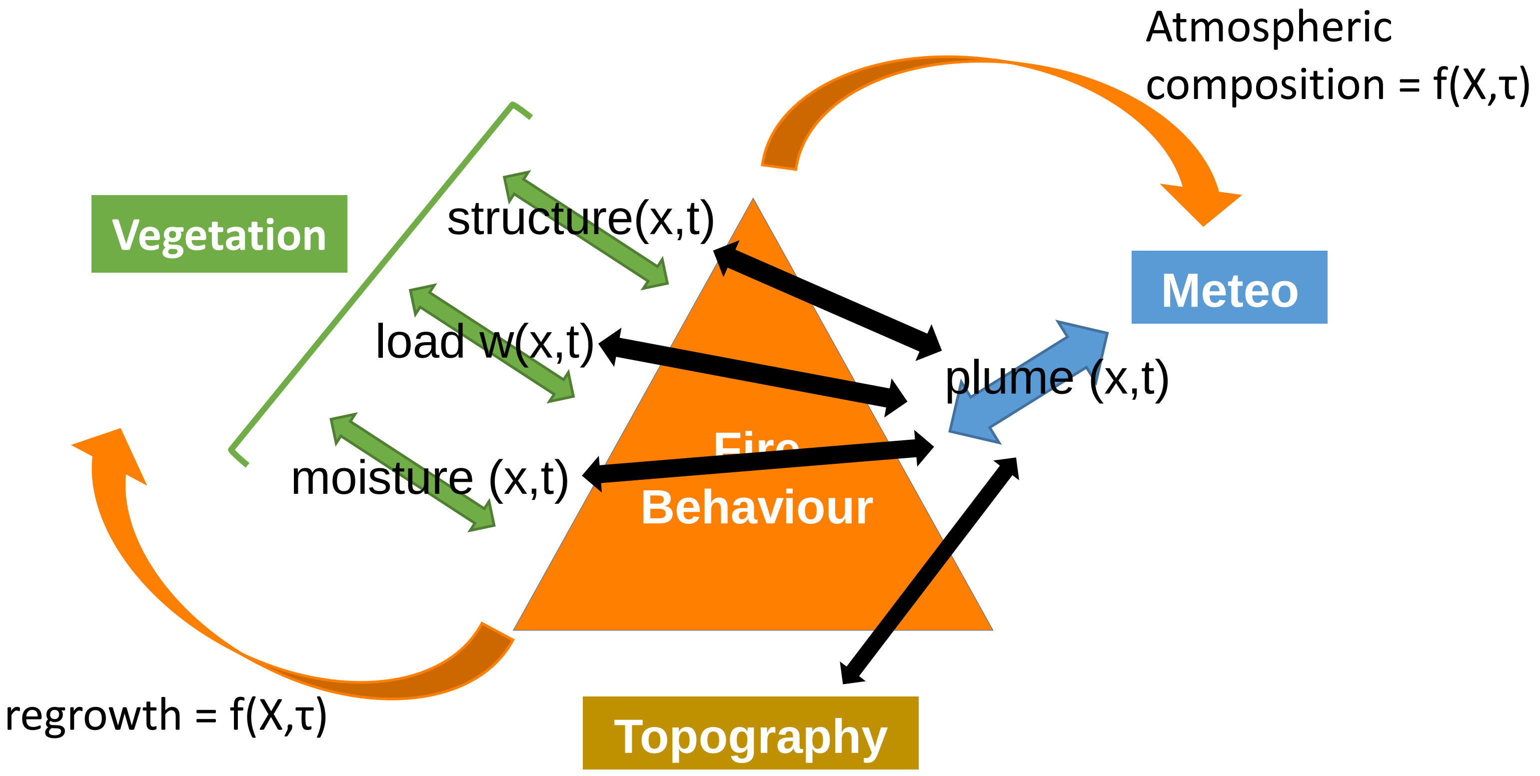
constant

FI = H w ROS

Rothermel

- Topo
- Ambient Wind
- Fuel Class [Scott and Burgan]

FI: Fire Intensity
H: Low Heat of Combustion
w: Fuel Load
ROS: Rate of Spread



FI = H w ROS(vegetation,plume)

most of the variability

X,τ: global, ecological time scale
x,t: fire behavior scales (meter, second)

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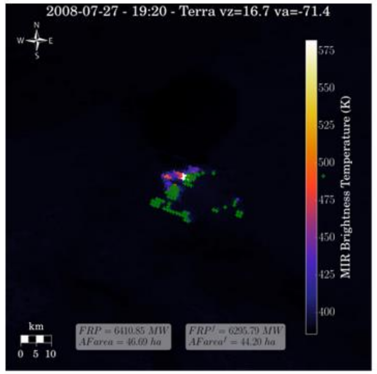
Introduction:

Fire observation Scales:

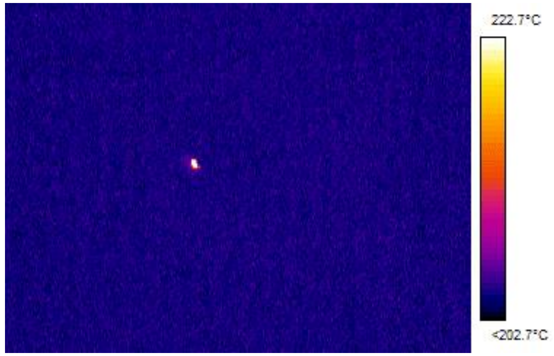
FRE:Fire Radiative Energy
FRP: Fire Radiative Power

Landscape Scale ⟷ Laboratory Scale



Fuel Mass Consumption [kg] = 0.368 FRE [MJ]

Wooster et al 2005

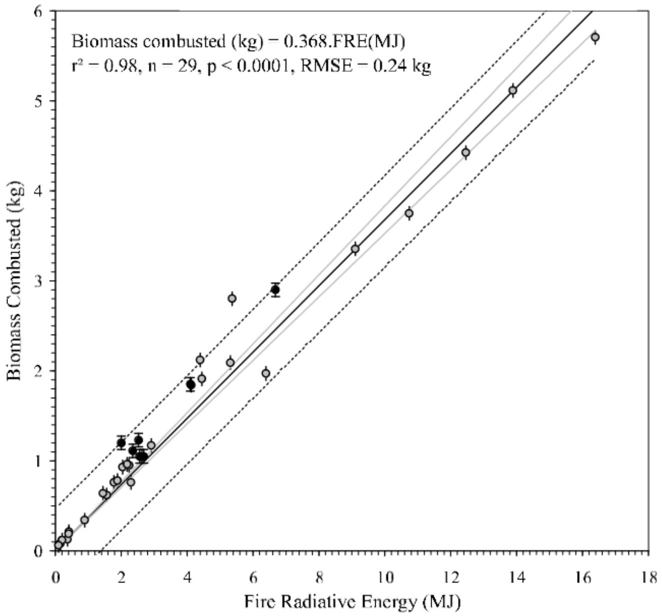


$$FRP_{TRUE} = \varepsilon\sigma \sum_{k=1}^{n} p_k T_k^4 \qquad [Wm^{-2}]$$

$$L_{f,MIR} \approx \varepsilon_{f,MIR} a T^4$$

$$FRP_{MIR} = \left(\frac{\sigma.\varepsilon_f}{a.\varepsilon_{f,MIR}}\right) L_{f,MIR}$$

- Lambertian source
- gray body
- Retrieve radiative flux from one wave length
- Absorption from atmospheric water vapor
- Background



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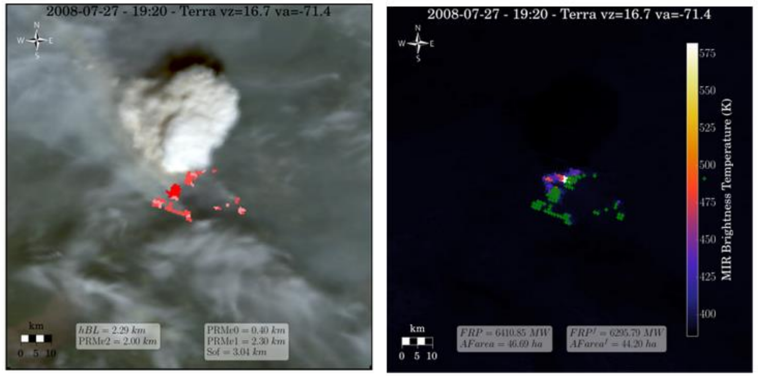
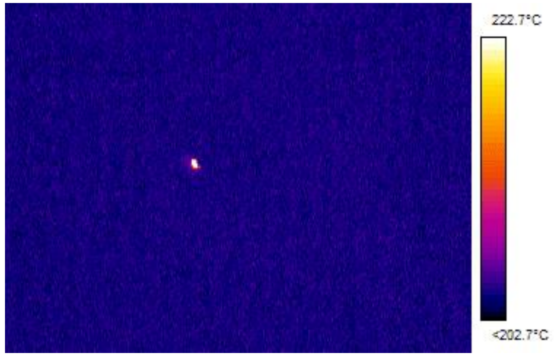
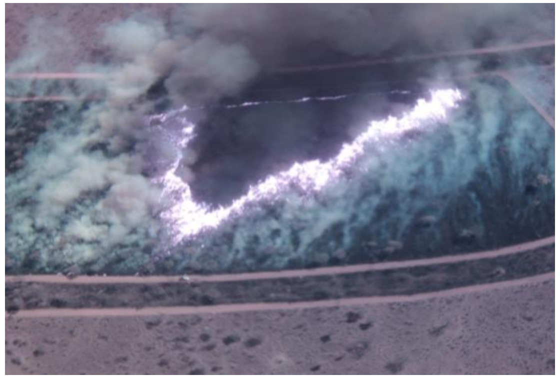


Fuel Mass Consumption = 0.368 FRE



Fire Field Scale



Can we used **airborne IR** fire observation and **atmospheric modeling** to compute **local Fire behavior [FB]** metrics and **wind field**.

Objectives:

1. Setting up a robust methodology for estimating fire behavior (FB) metrics at high spatial and temporal resolution [1m, 1Hz]
   (a) orthorectification
   (b) segmentation
   (c) computation of FB metrics
2. Using local FB [flaming + smoldering] to simulate wind flow
   The Fire Burner methodology: convert FB to Heat release Rate Map

Fire behavior metrics:

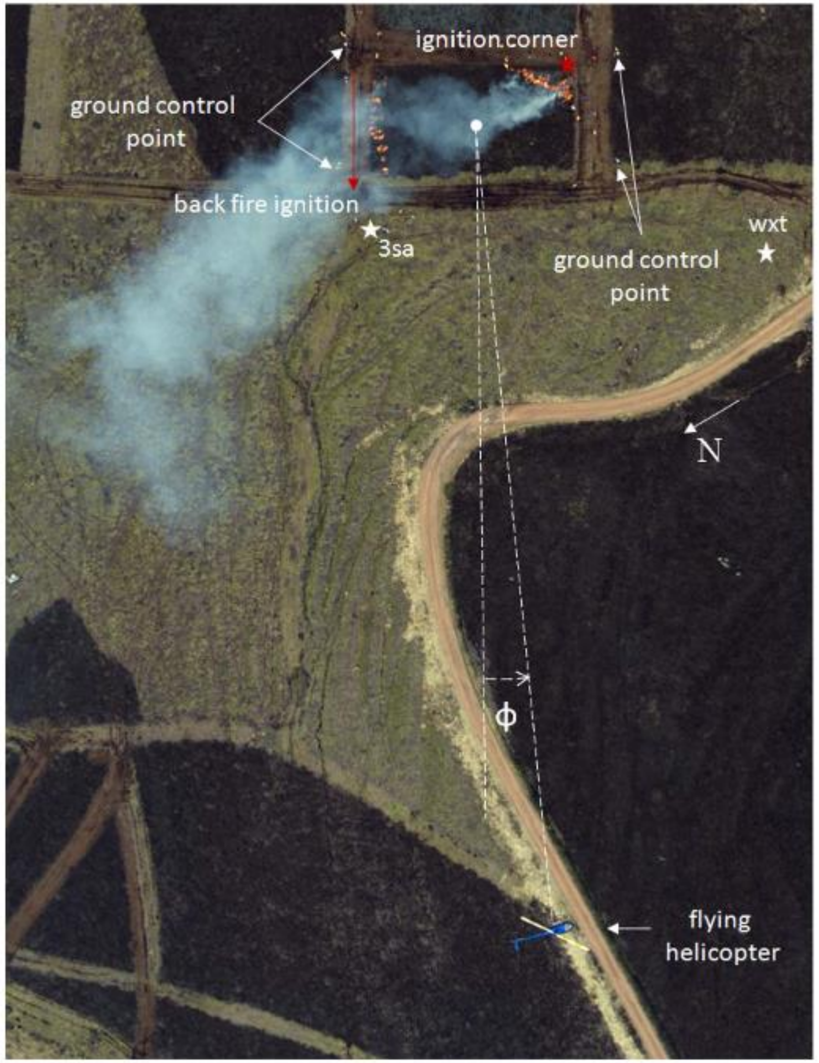
- ROS (m/s)
- Flame Depth (m)
- Burning time (s)
- Flaming Residence time (s)
- FRP (kW)
- FRE (kJ)

Introduction:

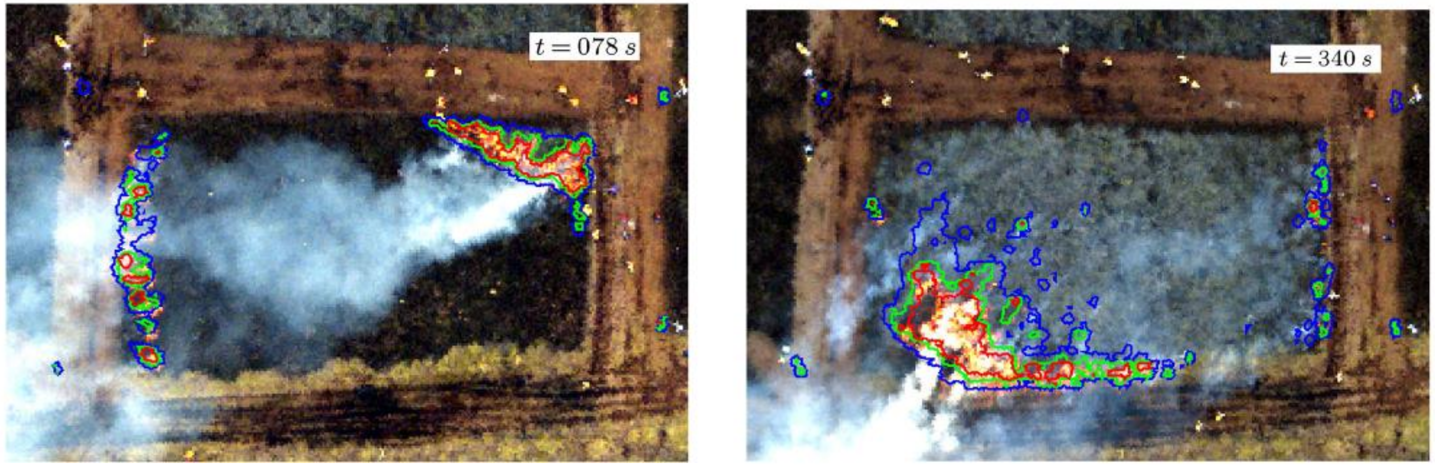
FRE:Fire Radiative Energy
FRP: Fire Radiative Power

Fire Field Scale

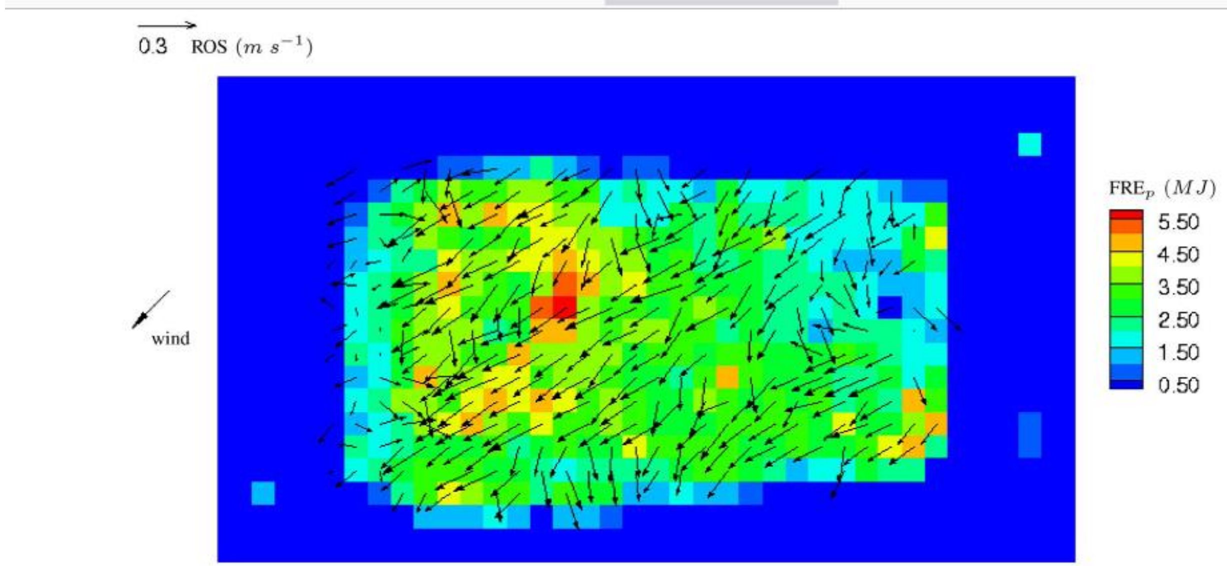
March 2010, UK Northumberland



Orthorectification



Fire Behaviour Metrics calucation

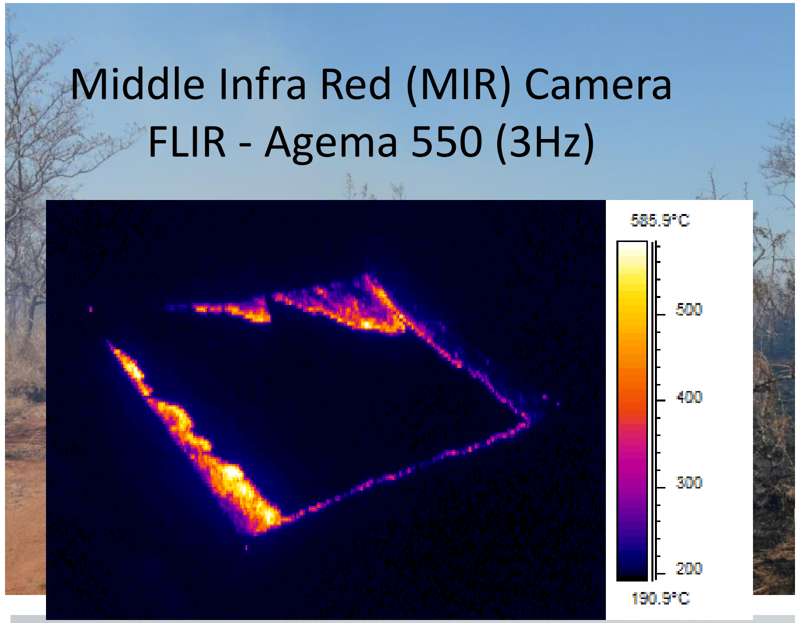


Fieldwork Campaign

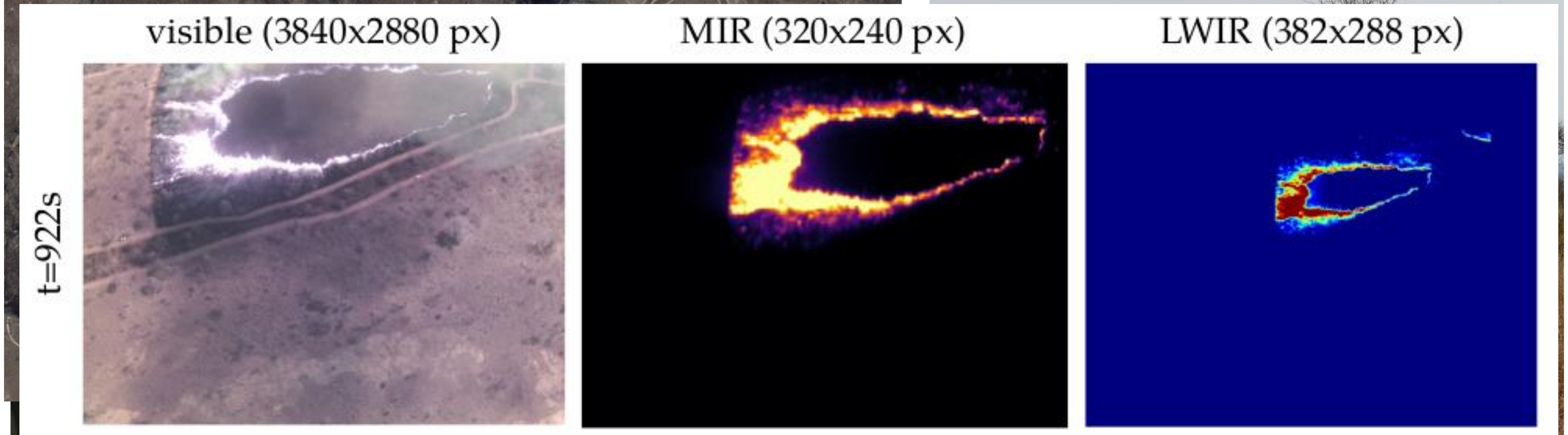
4 burns conducted in 2014 in Kruger Natioanl Park.
Operated from the helicopter:

King's College London
University of London

- MIR Camera (FLIR Agema 550, 3Hz, T>470K)
- LWIR Camera (Optris 400, 1Hz, 270-900K)
- visible GoPro with IR filter removed



•Pause of the cameras are unpredictable
•Cameras do not the same **field of view**
•Their relative **pointing directions** are not fix
•They are only **nearly synchrnized**
•No geometric cameras calibration



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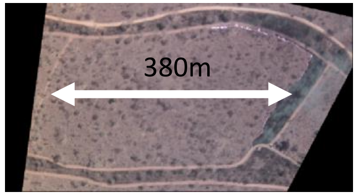
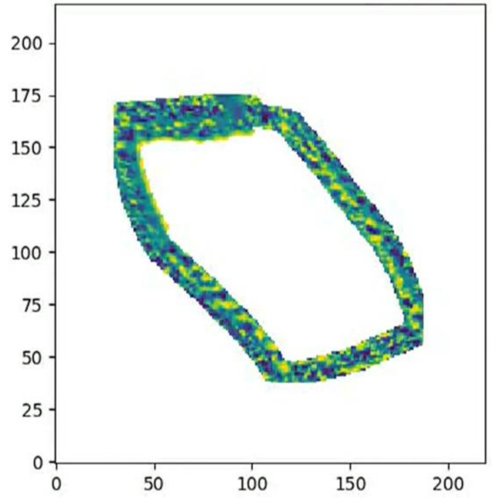
Georeferencing LWIR



Shabeni1:
- No Corner Fire
- Intense fire

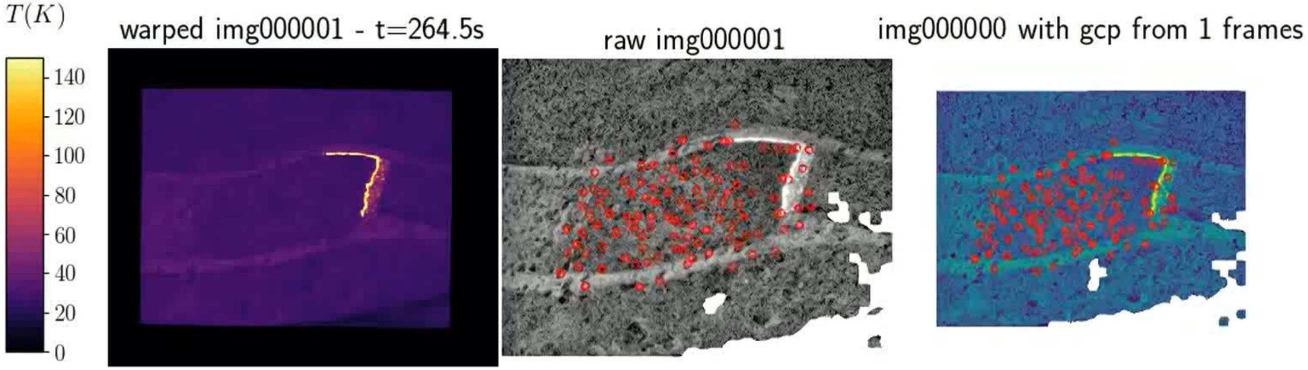
- No fix Ground Control Point (Corner Fire)
- Flat terrain
- Use Ground Control Points only on the first image
- Compute homography matrix to warp image with the combination of
  - a **feature-based** method (Lucas–Kanade of *n* last processed images as a template
  - a multi-resolution **area-based** (Enhanced Correlation Coefficient, ECC) method using **one reference** image as a template.

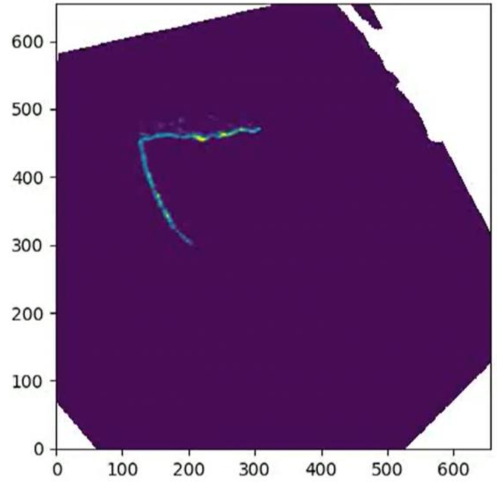
2nd step: Georeferencing + Optimization to correct for parallax effects using feature in the cooling vegetation



3rd step: Filtering on SSIM time series. 20% of the original images are removed

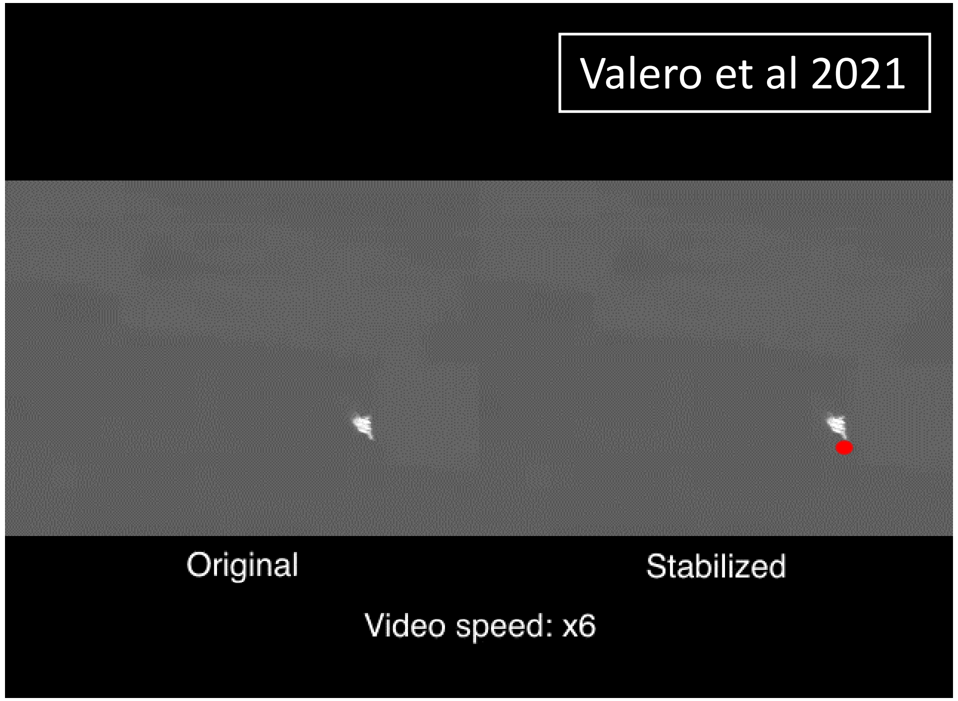
1st step: 530 images warped in 2.5h

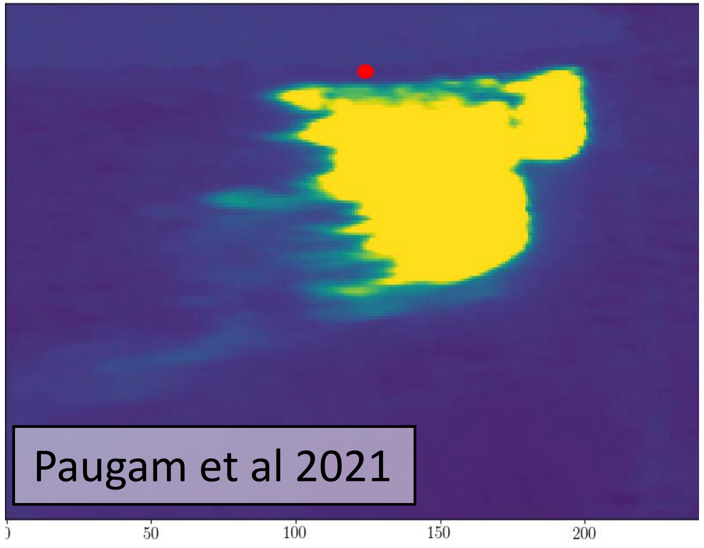




Georeferencing LWIR

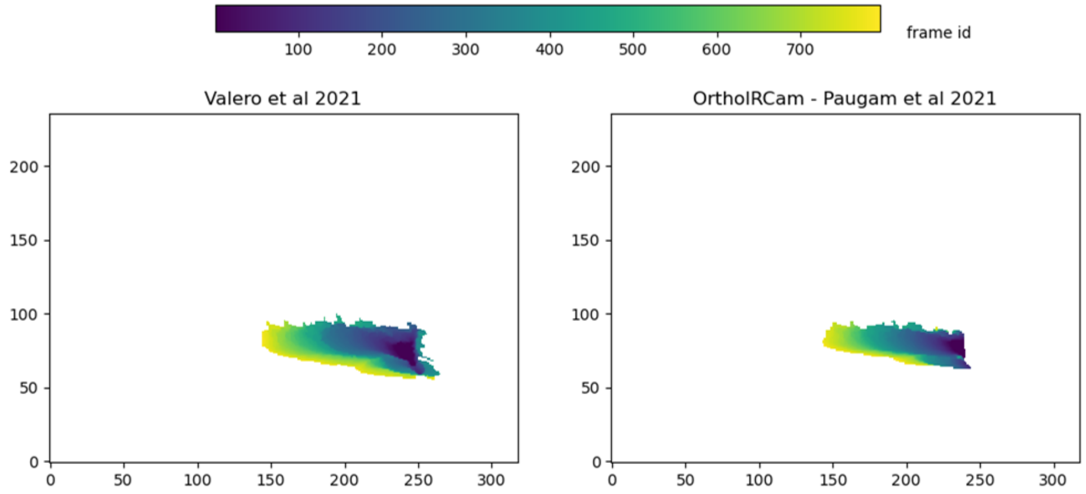
Comparison with existing algorithm

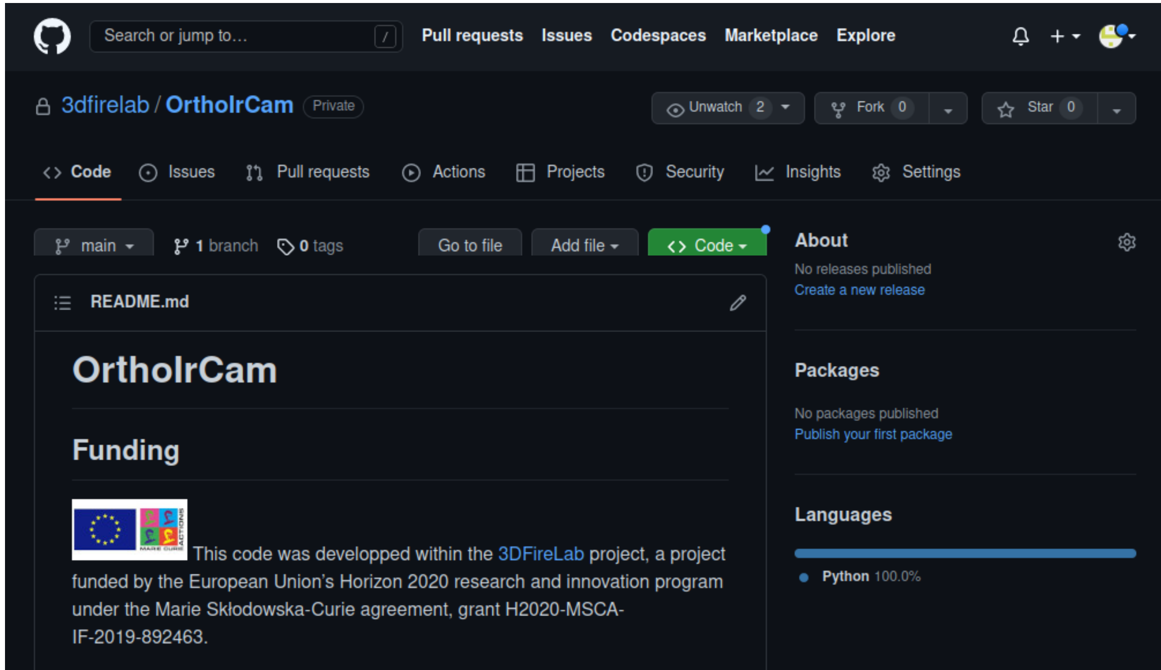




5Hz frame rate showing in real time

https://github.com/3dfirelab/OrthoIrCam



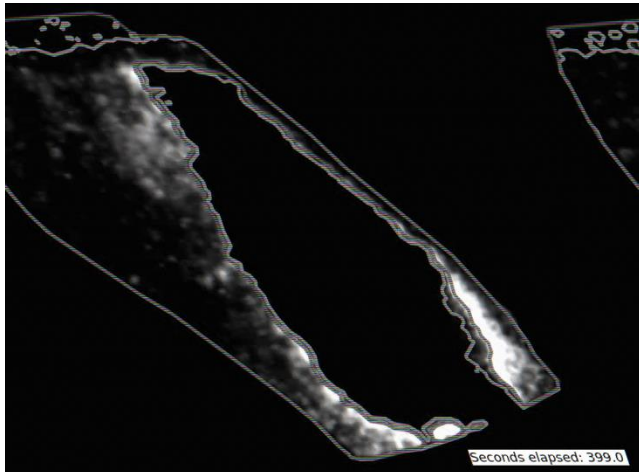


Fire Front Perimeter Segmentation

A Deep Learning approach: C. Lapeyre & N. Cazard

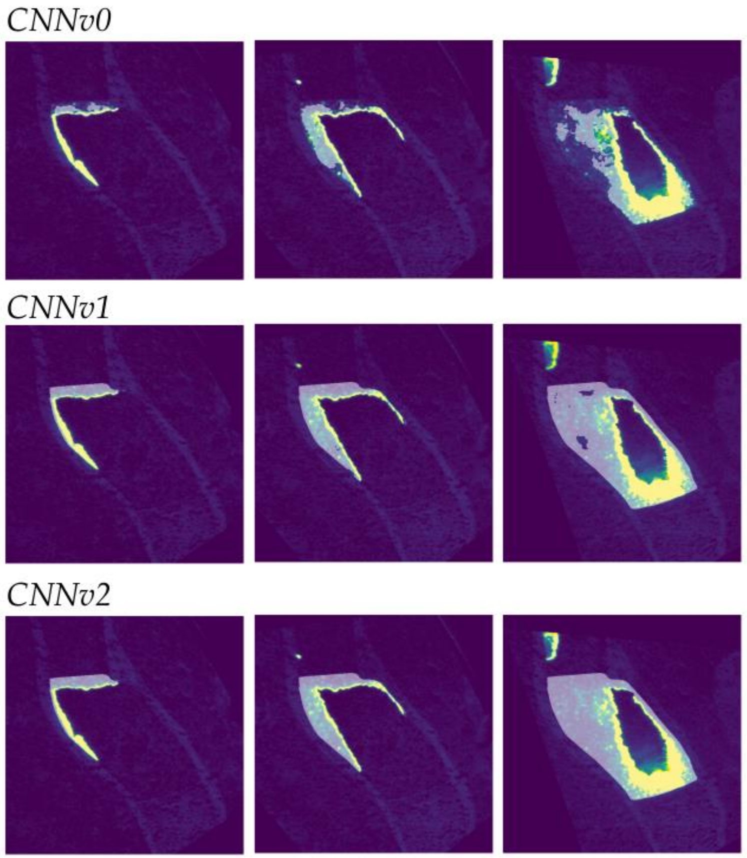
Constraint: Fire Front segmentation using only one image

Challenge: training a neural network with a small data set counting initially **10 manually annotated front**



Threshold
Deep Learning

Series of CNN



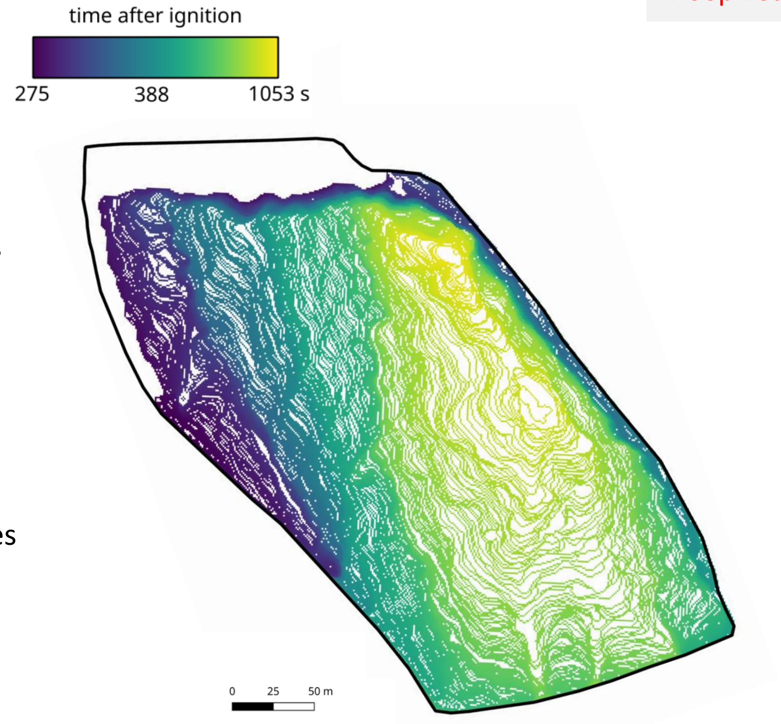
- 10 images with high representation of active front
- 1 layers
- CCN input is radiance

CNN*v0* + arrivalTime Map → 50 tagged images

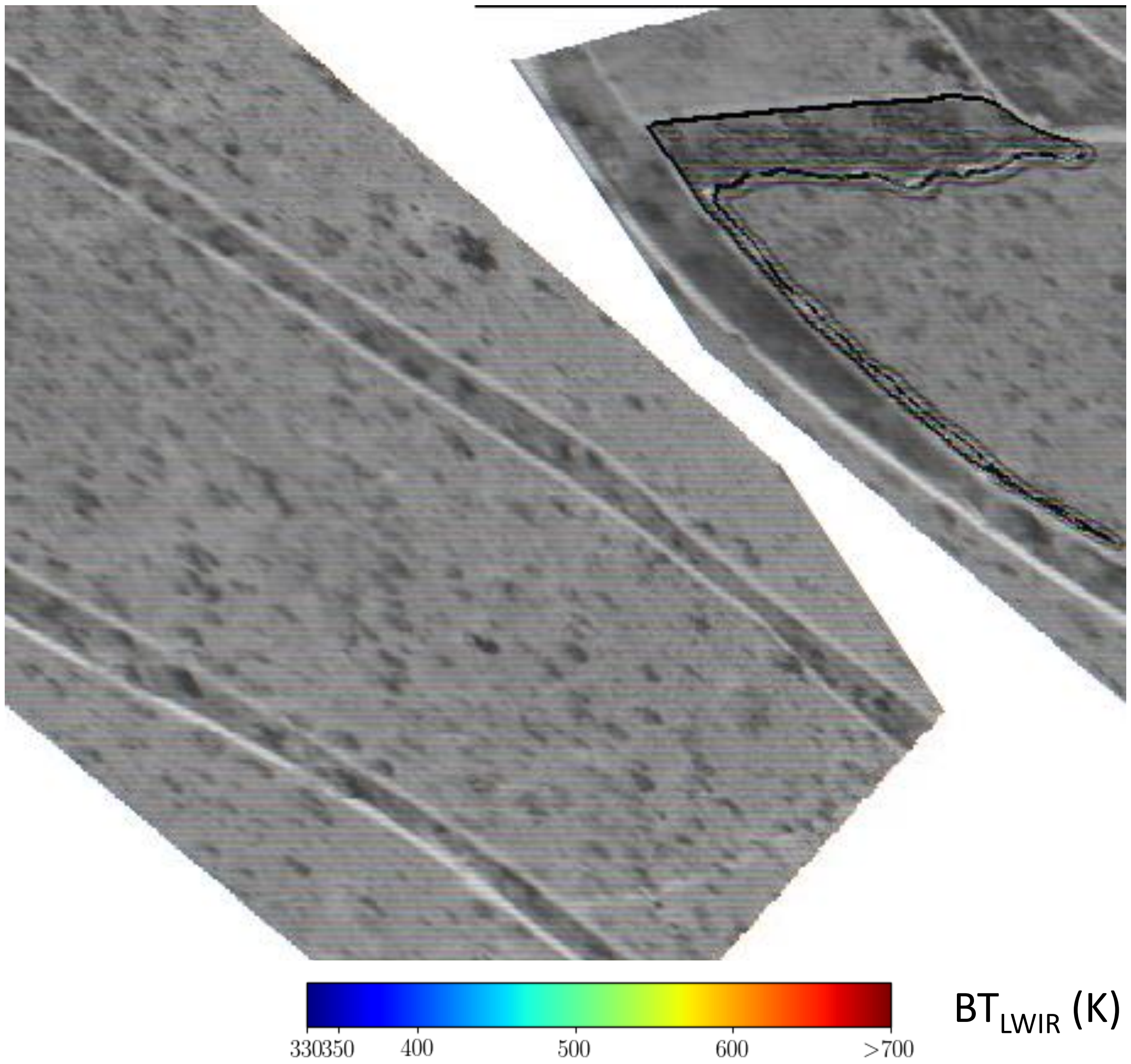
CCN inputs channels are now radiance + plot

CNN*v1* → 100 tagged images

CCN input are Brightness temp. + plot



Georeferencing + Segmentation



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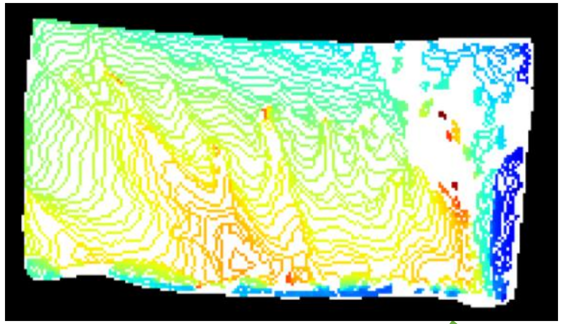
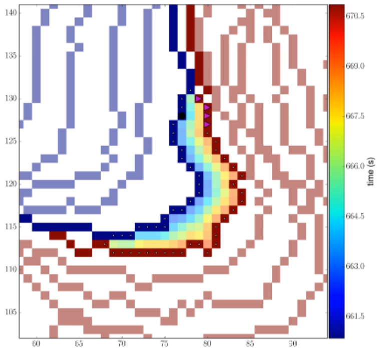
Rate Of Spread (ROS) calculation

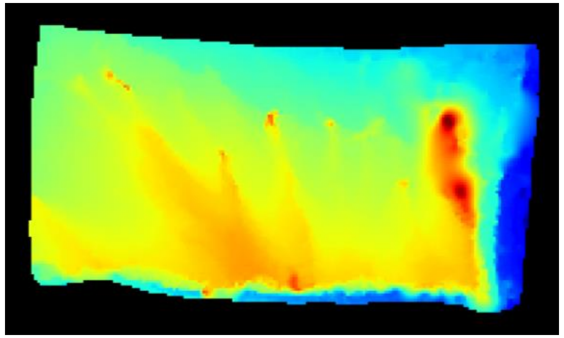
Fill Up the Gaps: Arrival Time Map



low time resolution

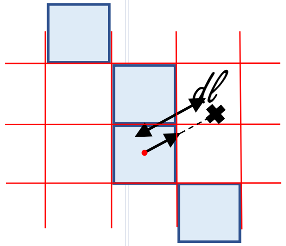


- linear Interp. along all possible path
- Radial Basis fct. interpolation



Fire Front ROS:

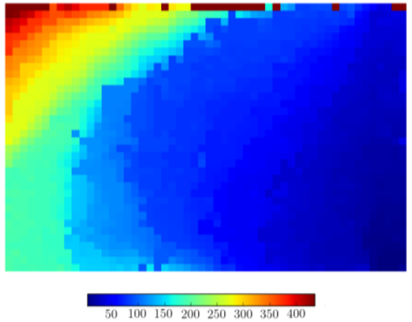
$$ROS(i, j) = dl / \Delta t \; n(i, j)$$



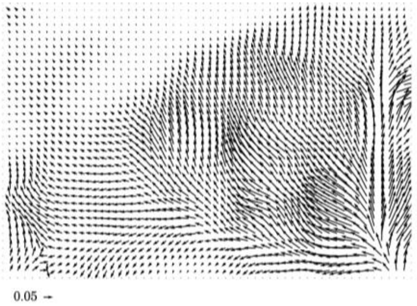
fire front at time t

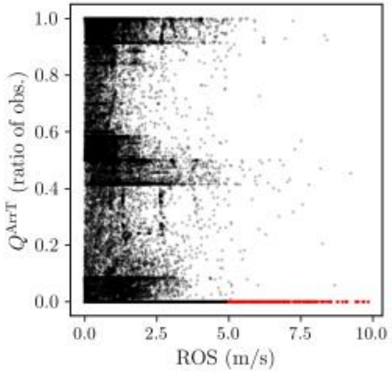
dl = grid resolution

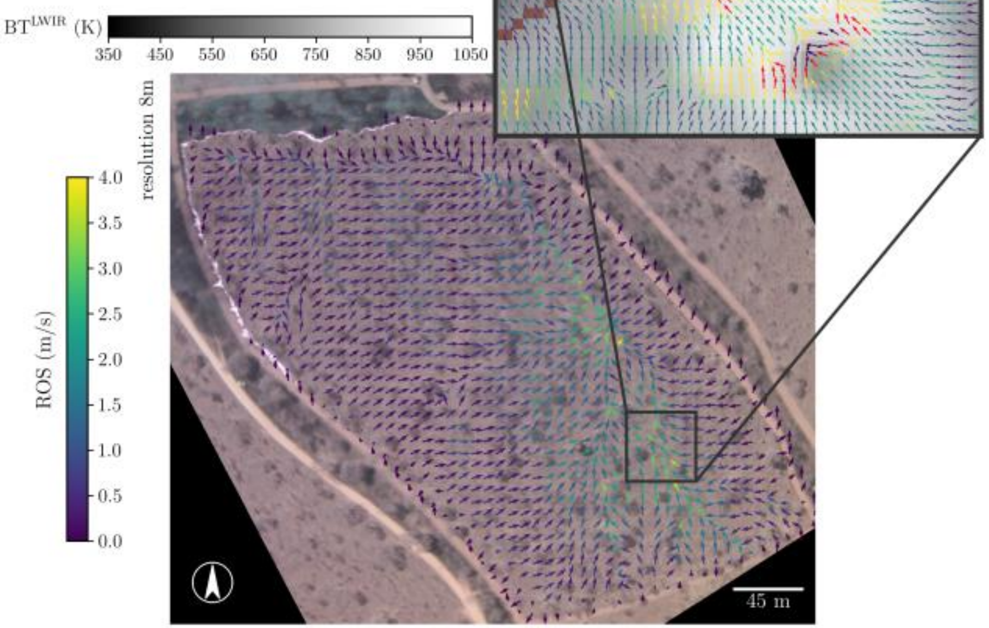
Arrival Time (s)



ROS (m/s)





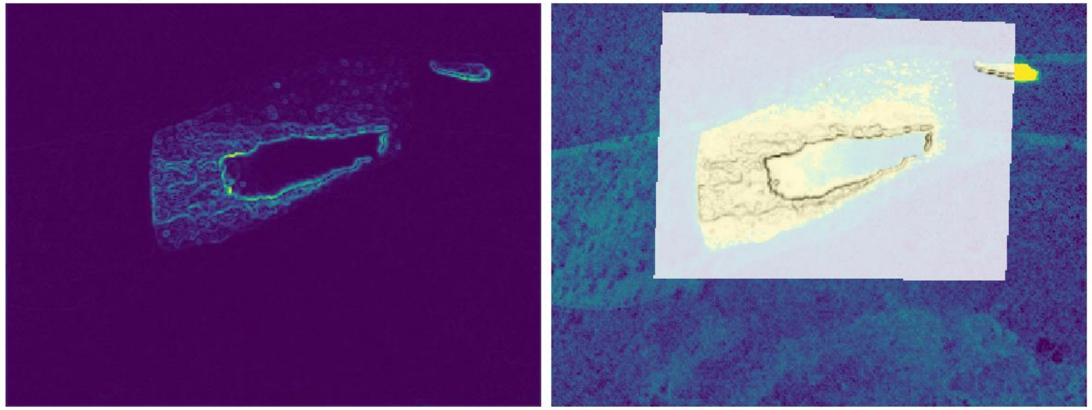


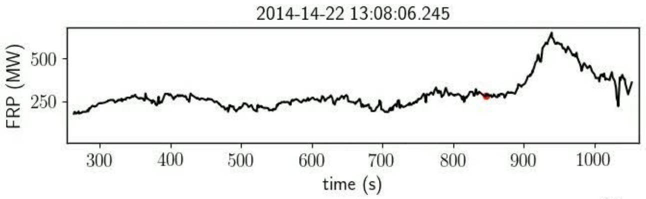
Georeferencing MIR & FRP Calculation

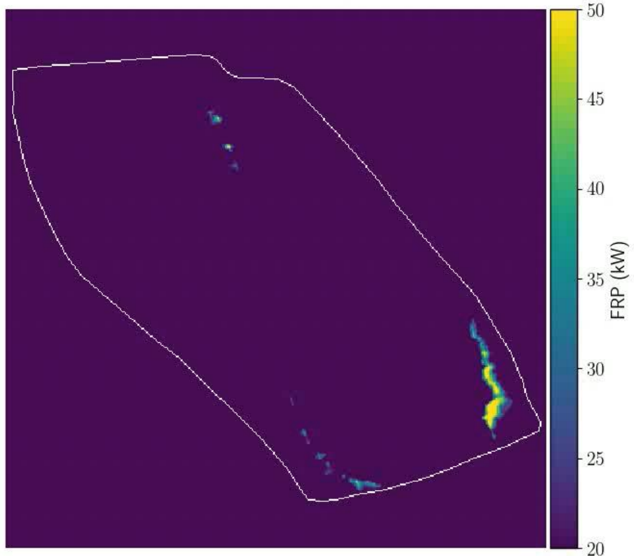
[Paugam et al 2021 – mdpi/remote sensing]

FLIR Agema 550 (12-bit imager). To assure radiometric precision in fire range temperature, camera is set on high gain, hence not detecting background. (T>470K)

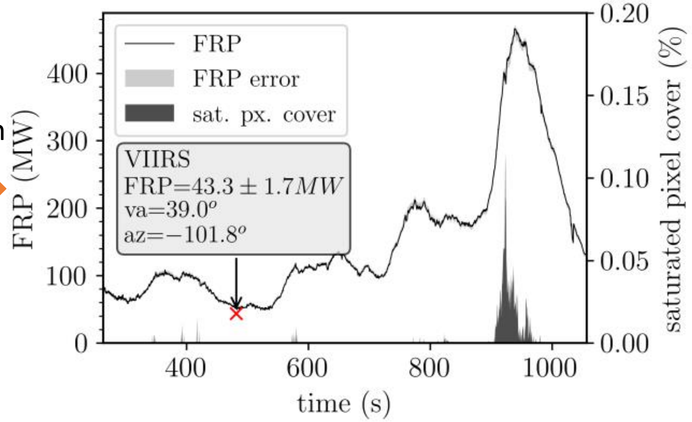
Warping MIR on LWIR using gradient

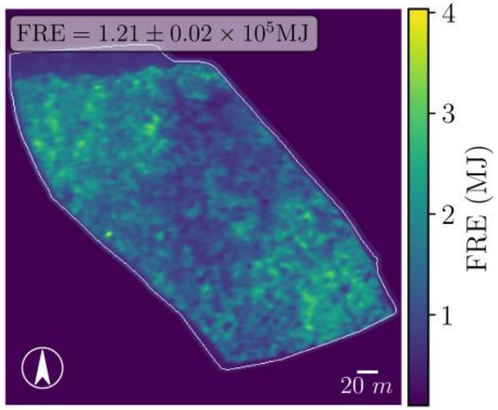


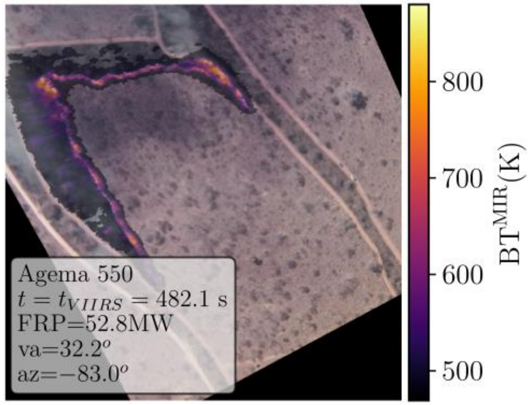




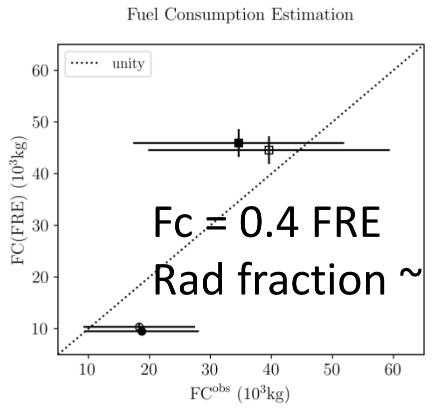
time integration

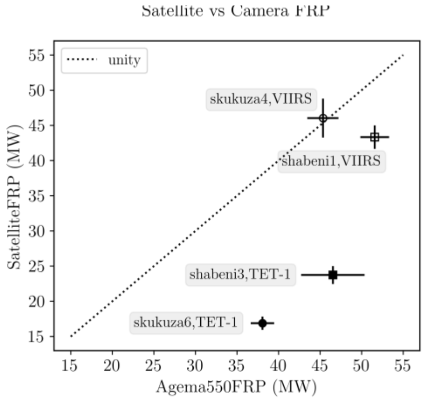






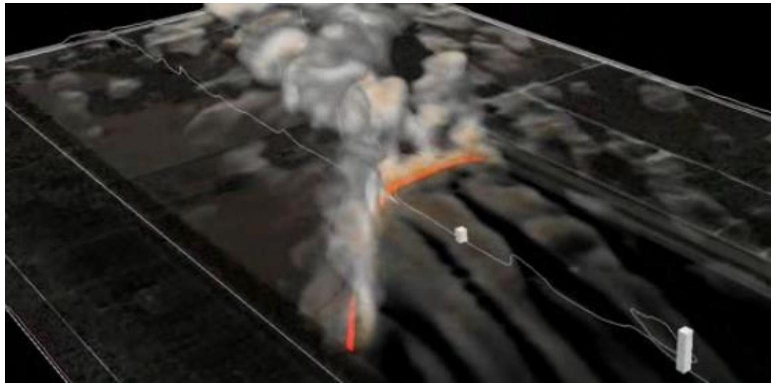
[Wooster at al 2005]





The Fix Burner Method & MesoNH-ForeFire

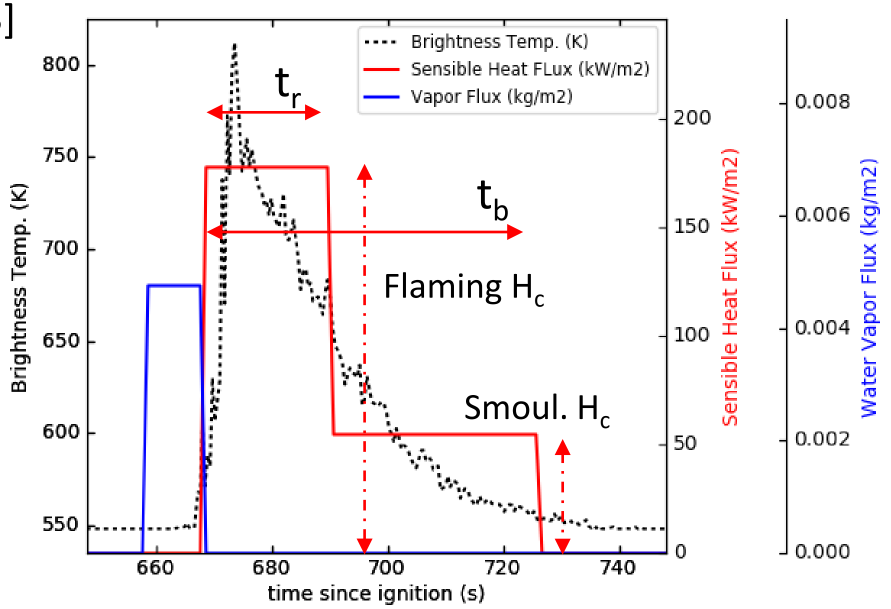
MesoNH:
- Non-hydropstatic (solve vertical wind)
- Anelastic (filter sound wave)
- LES Scheme (subgrid turb. based on TKE)
- Microphysic (water phase change)
- Nested model (large scale effect)
- Chemistry (O_3, Nox,)



Fire Flux Experiment simulation [Filippi et al 2013]

ForeFire (dx ~ 1 m): [Filippi et al 2009]
- Semi-physical fire spread model (fire=tilted radiant panel), [Balbi et al 2009]
- Flux Coupling Scheme which ensures energy conservation between Forefire and host meshes
- Output Water Vapour, Scalar, & Sensible Heat Fluxes

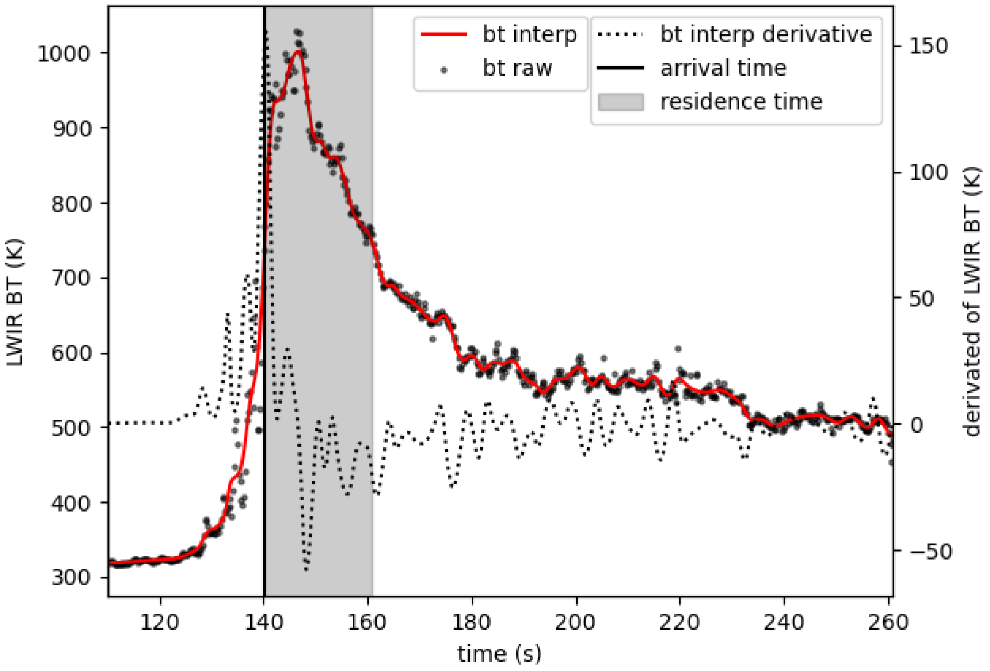
new Flux Model in ForeFire:
- force Sensible Heat directly from Observation.
- Assume a radiative fraction of 10%.
- Scalar Flux control with Emission Factor
- Water Vapor emitted ahead of the front

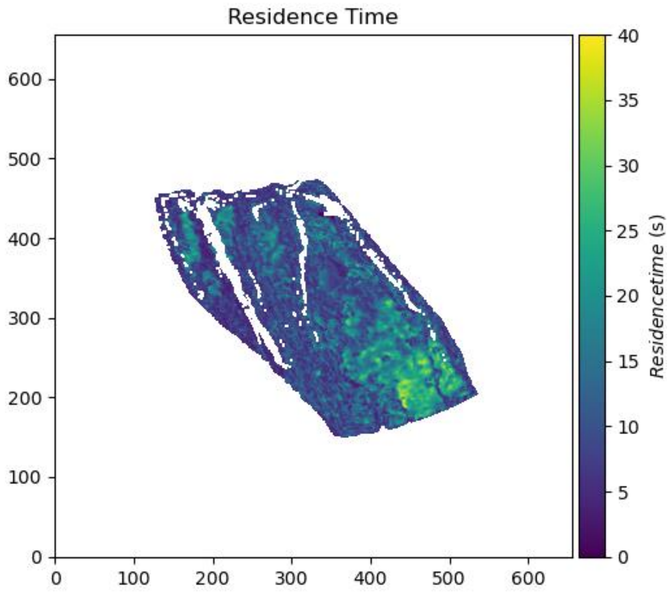


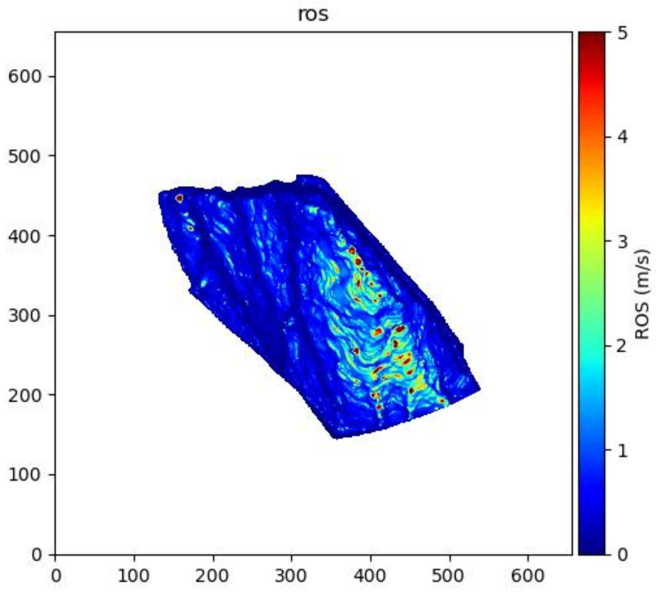
Residence Time τ & Flame Depth F_d

Compute τ from time series of BT and BT derivative.

High frame rate is crucial



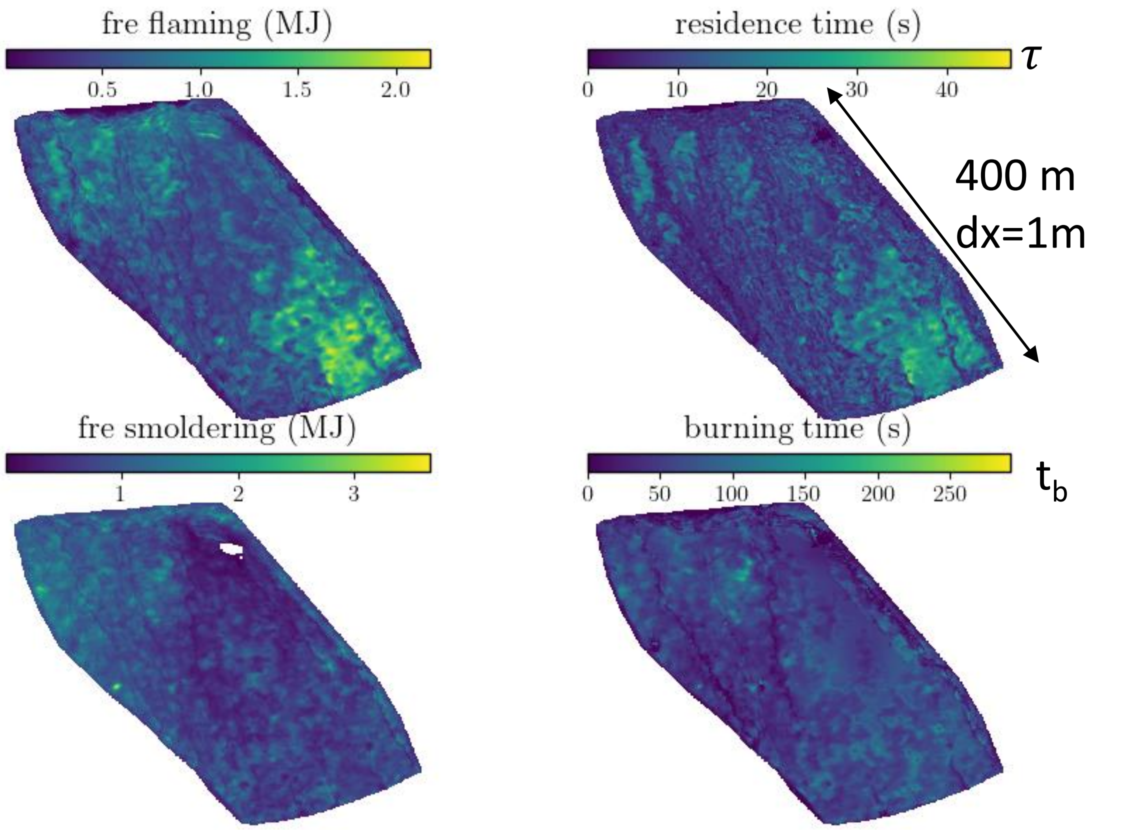


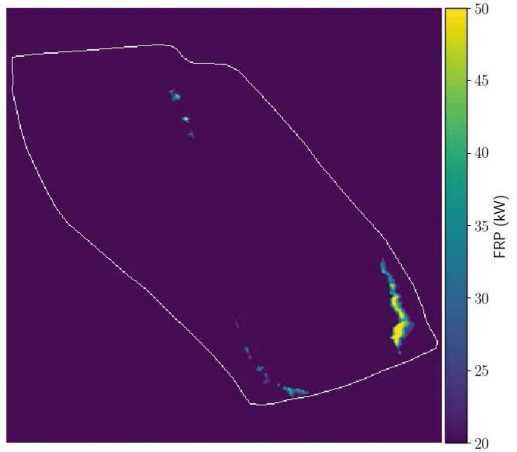


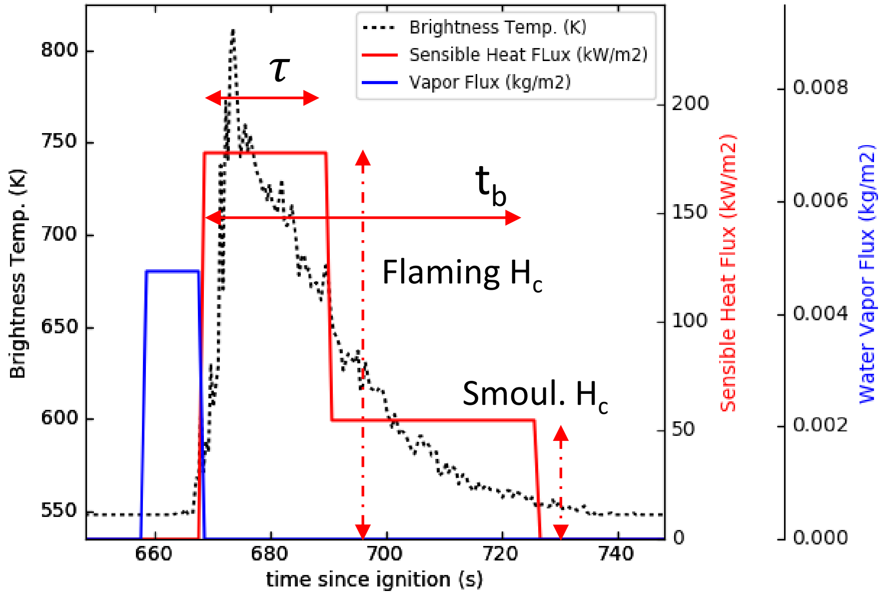
The Fix Burner Method: Input data

Shabeni1

MIR
1m resolution



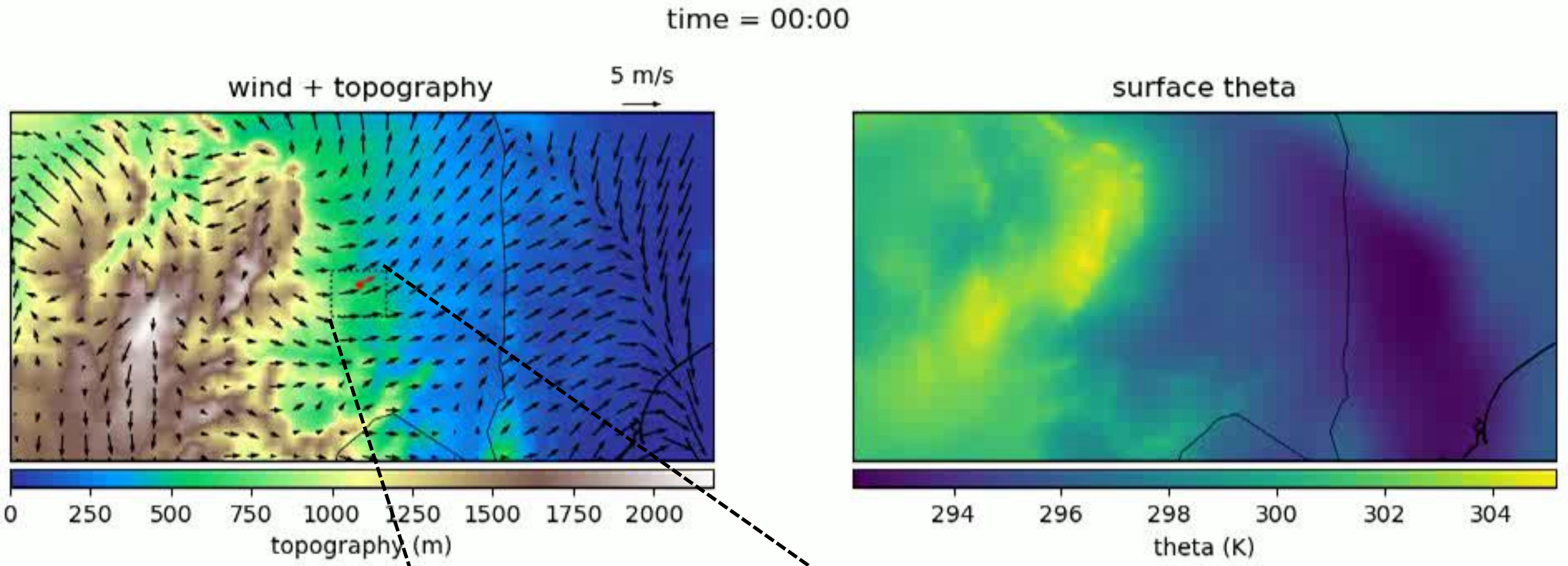




MIR → FRE_f, FRE_s → temporal map of Sensible Heat Flux

The Fix Burner Method: ambient condition

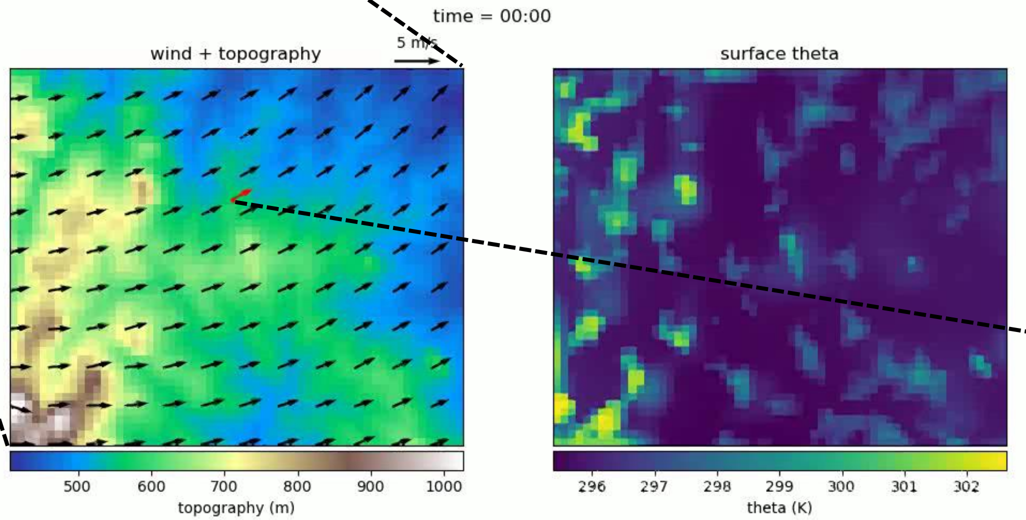
Reanalysis
Era-Interim
22-08-2014

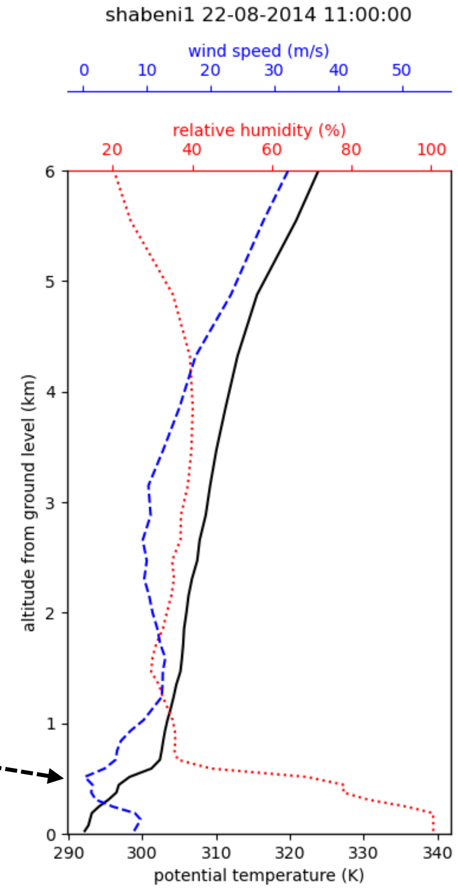


375 km, dx=2.5km

Downscaling simulation using
MesoNH Real Case capability

30 km
dx=500 m

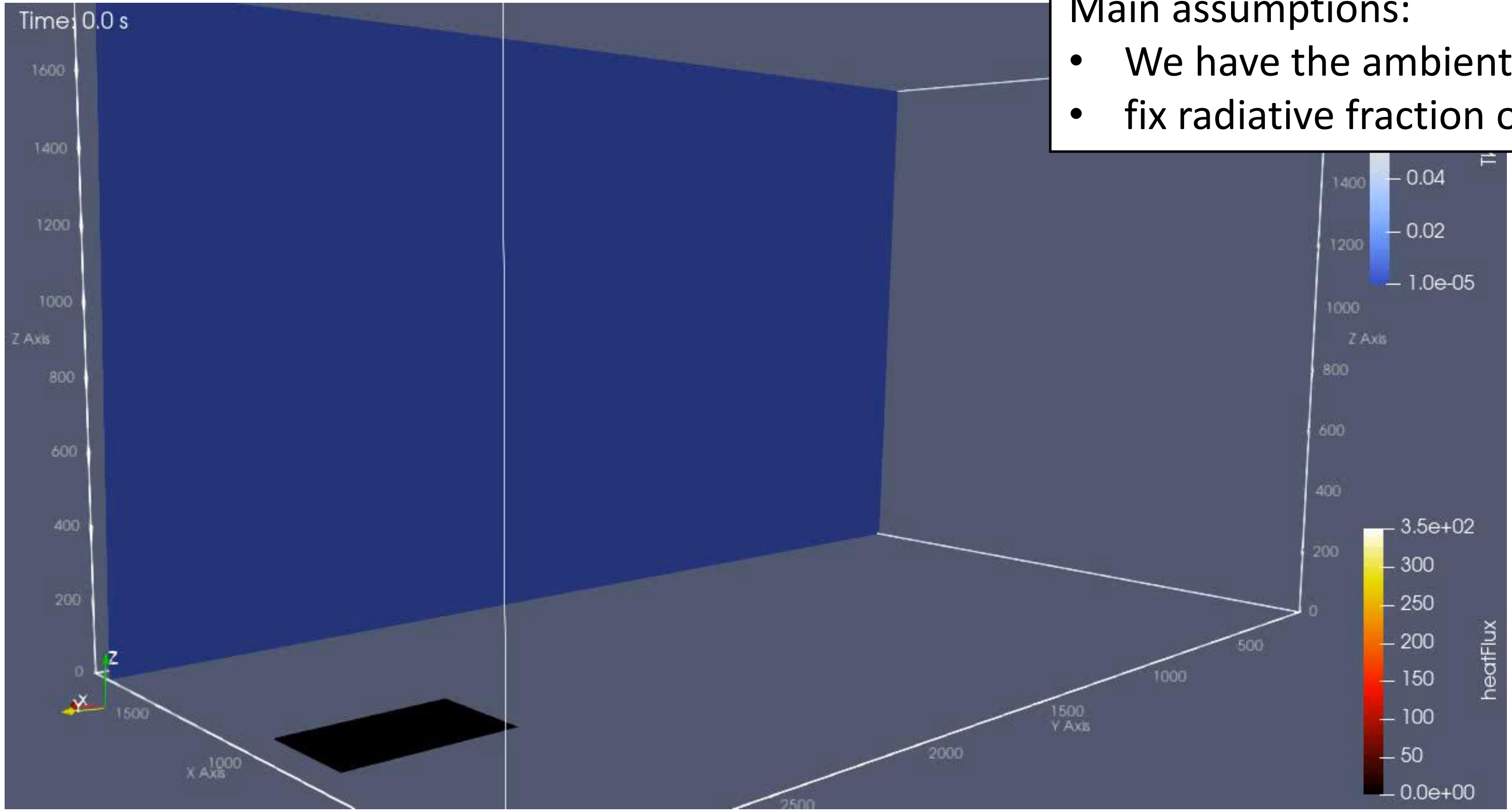




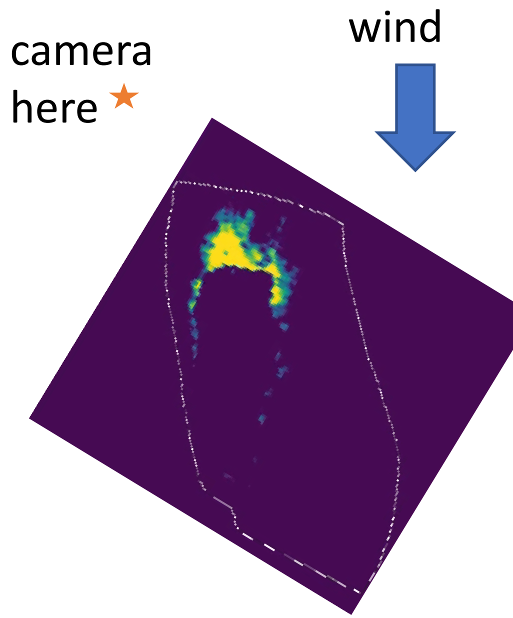
The Fix Burner Method

Main assumptions:

- We have the ambient wind correct, (eg no wind shift)
- fix radiative fraction of 10%



Isocontour is a passive scalar

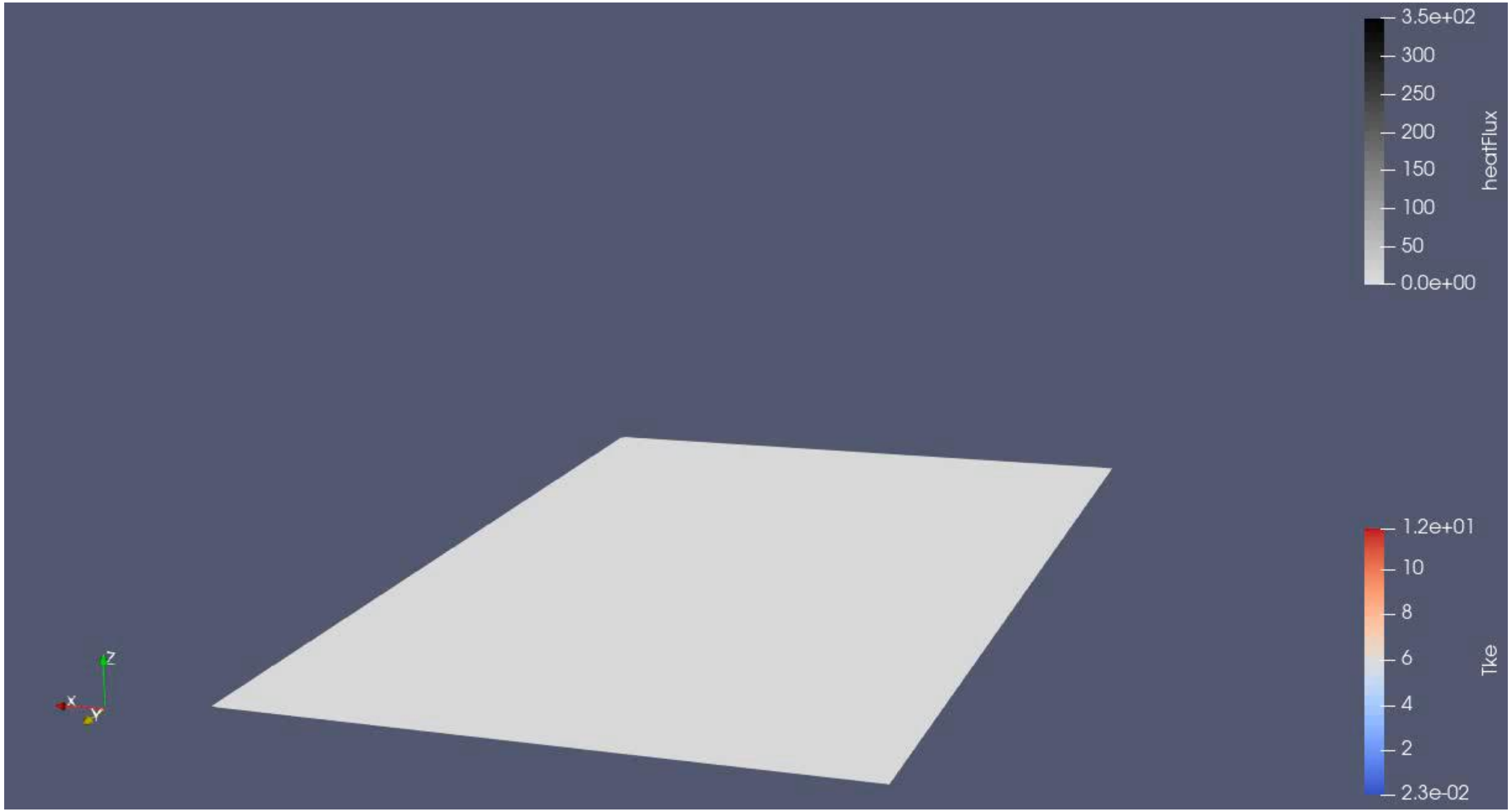


- No Microphysics
- Constant fuel Moisture
- 3 nested model: dx,dy,dz=32, 8, 2 m
- Sensible Heat Flux at ground level is directly estimated from the MIR camera
- Water vapour is released ahead of the fire front
- Arbitrary passive scalar emitted with emission factor adapted to flaming and smoldering regime

2m resolution inner model

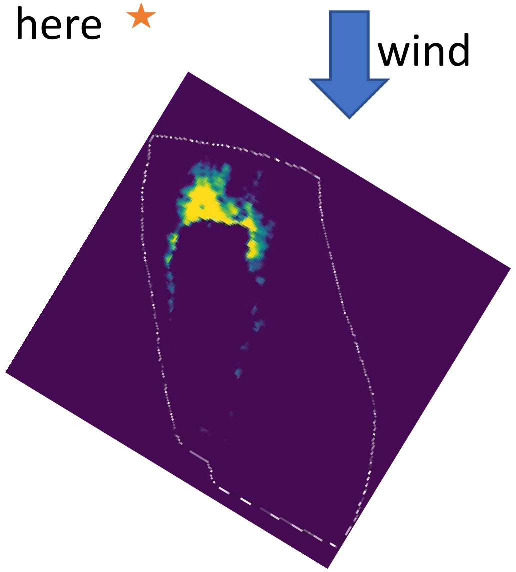
MesoNH simualtions are run at CERFACS

Animation is showing Isocontour of lambda-2 criteria (min of pressure)



camera here ★

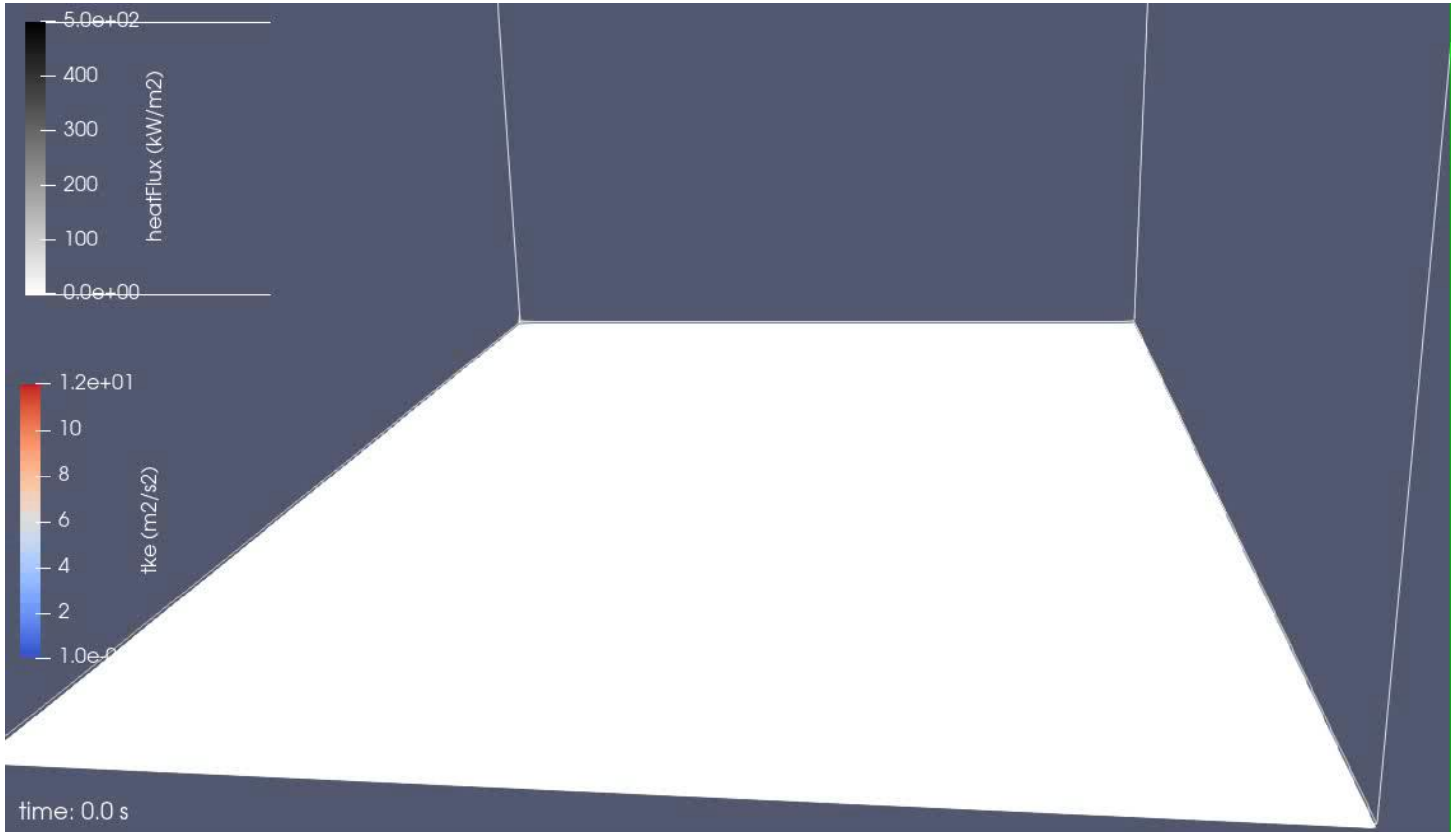
wind

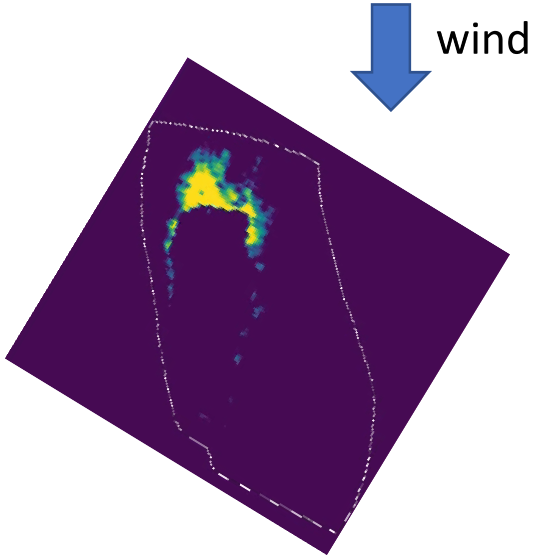


The Fix Burner Method

MesoNH simualtions are run at CERFACS

Animation is showing Isocontour of **lambda-2 criteria** (min of pressure)

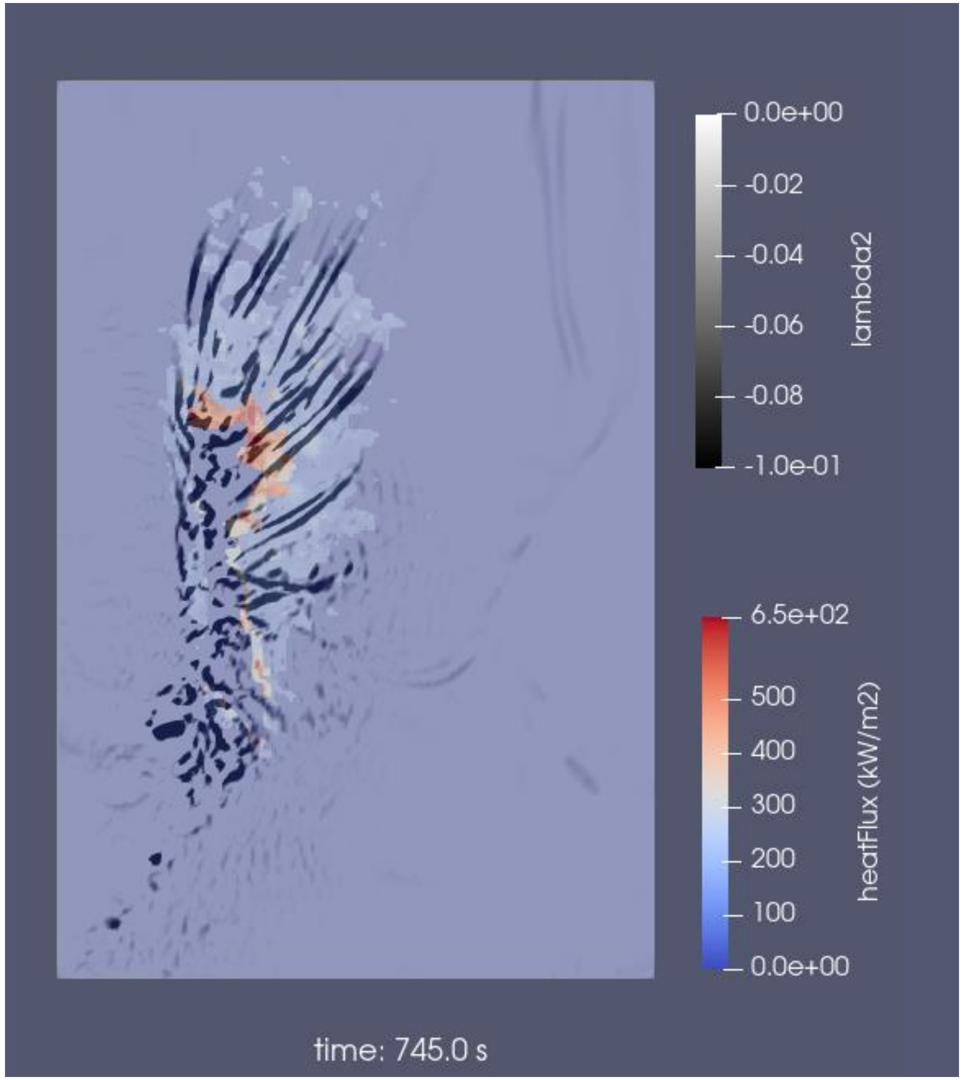




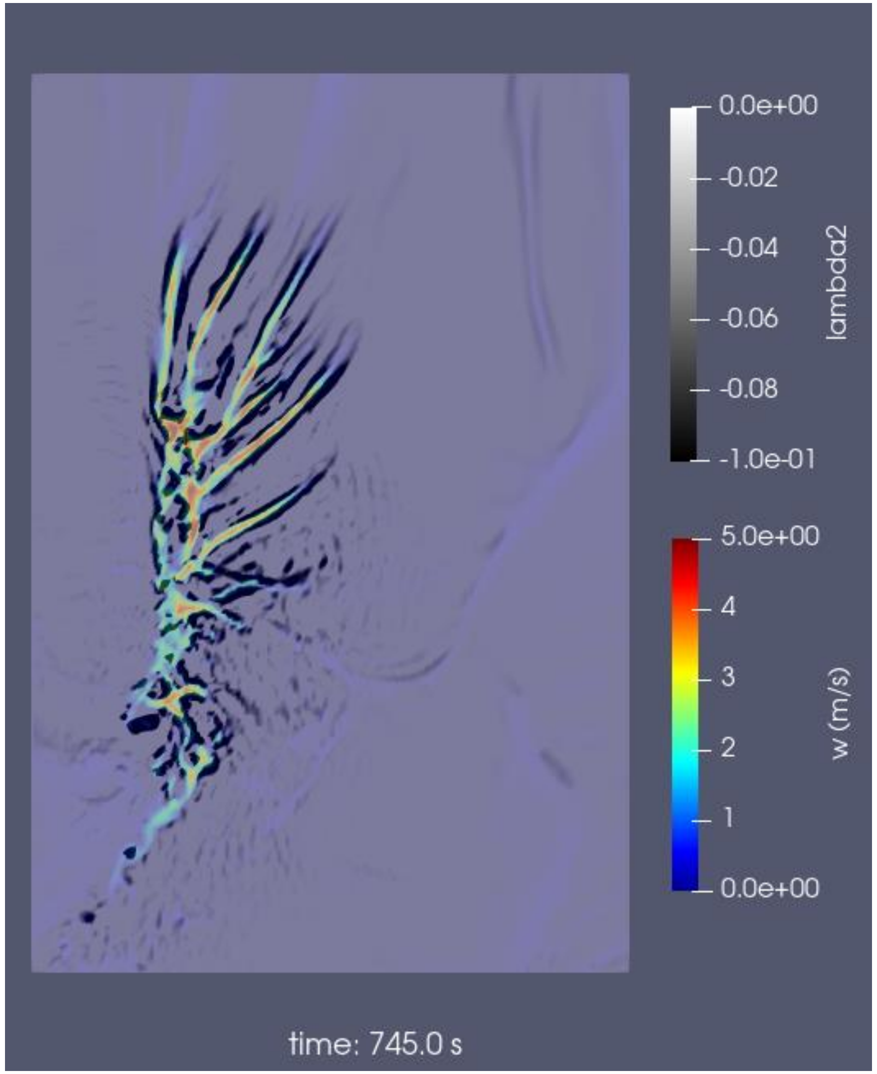
- Counter rotating vortex pair oscillate and form vortex ring
- Formation of tornado structure downwind name fire whirls

★ camera here

The Fix Burner Method



Heat Flux

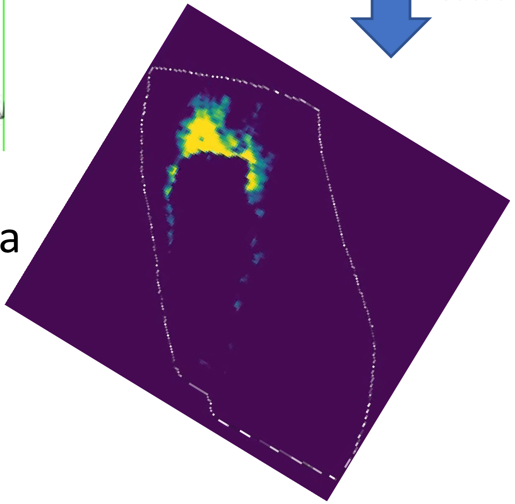


w

The Fix Burner Method

Animation is showing Isocontour of **lambda-2 criteria** (min of pressure)

wind

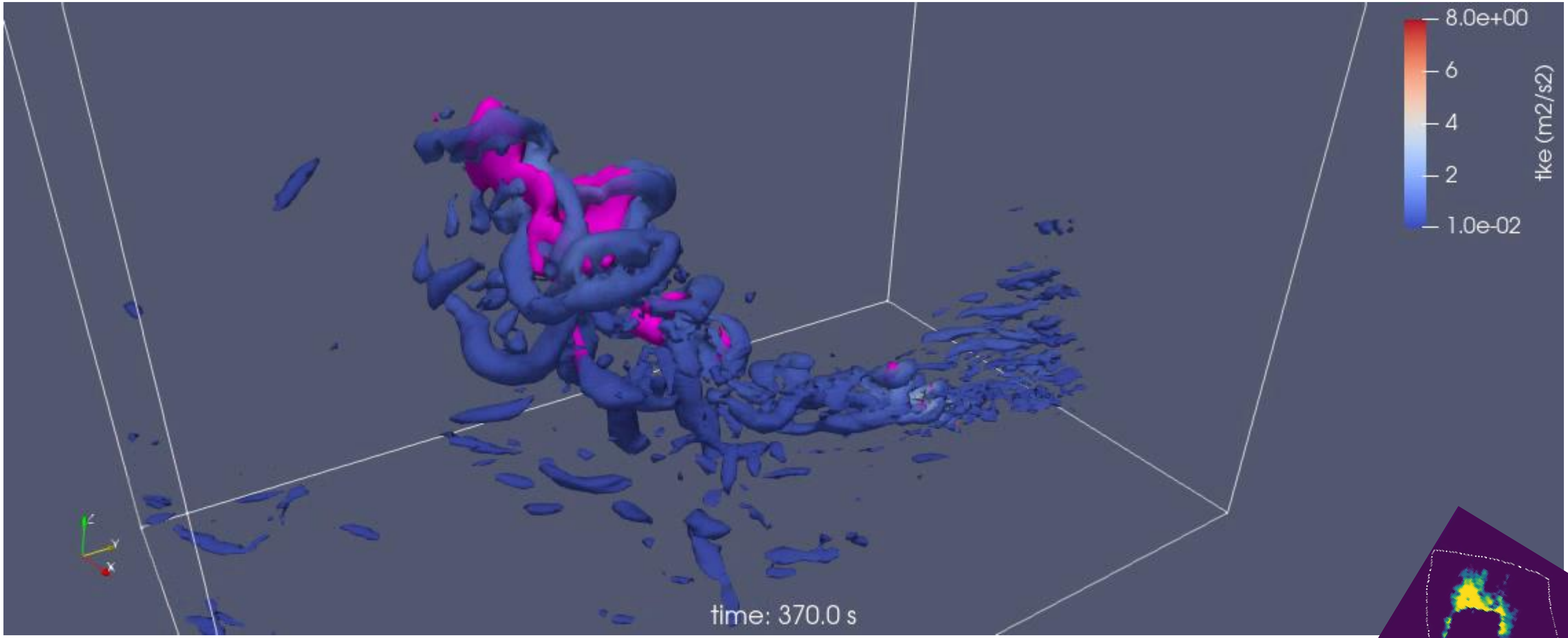


★ camera here

- Vortex ring
- fire whirls

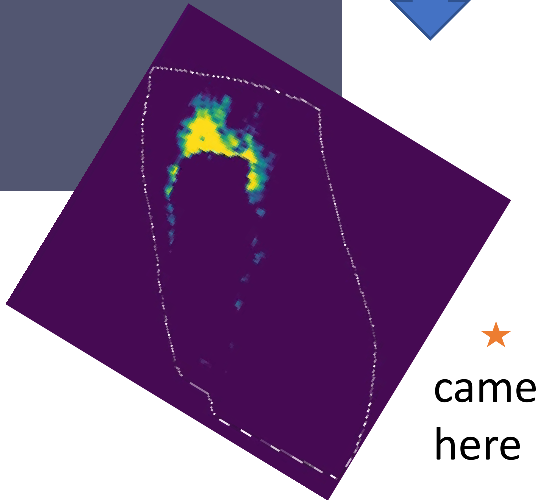
still exist at larger scale (model 2, dx=34 m, L=2km)

The Fix Burner Method



pink contour = vertical velocity w =5m/s

wind



camera here

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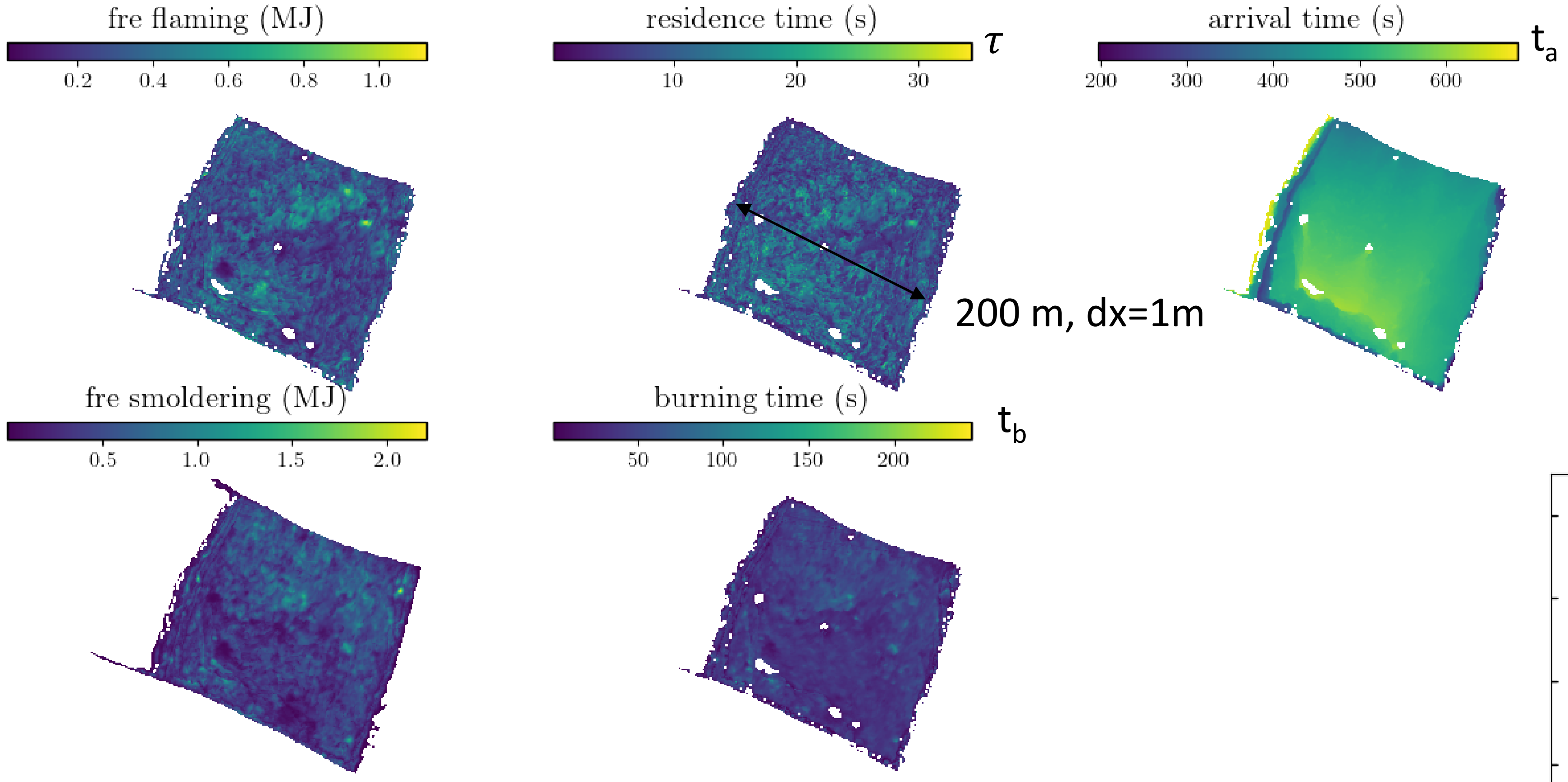
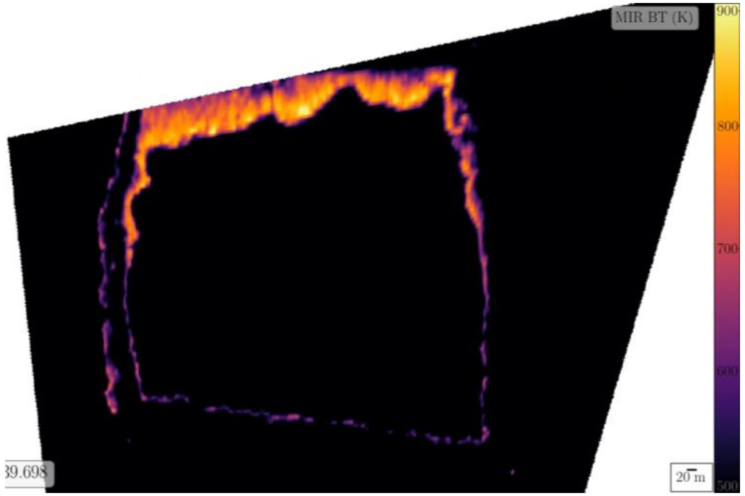
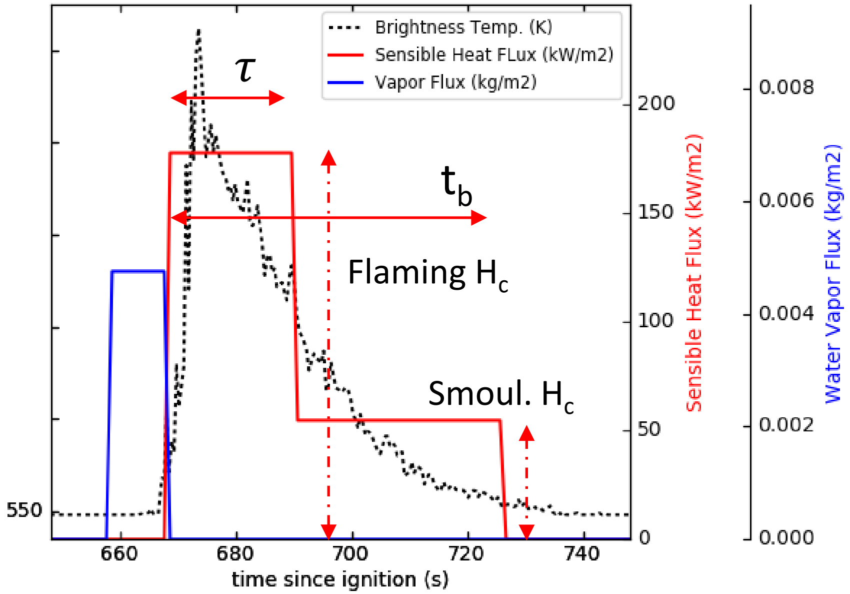
The Fix Burner Method: Input data

MIR, 1m resolution





Skukuza 4



MIR → FRE_f, FRE_s → temporal map of Sensible Heat Flux

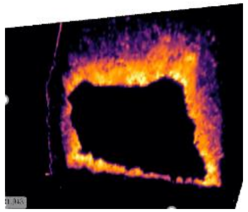
2m resolution inner model

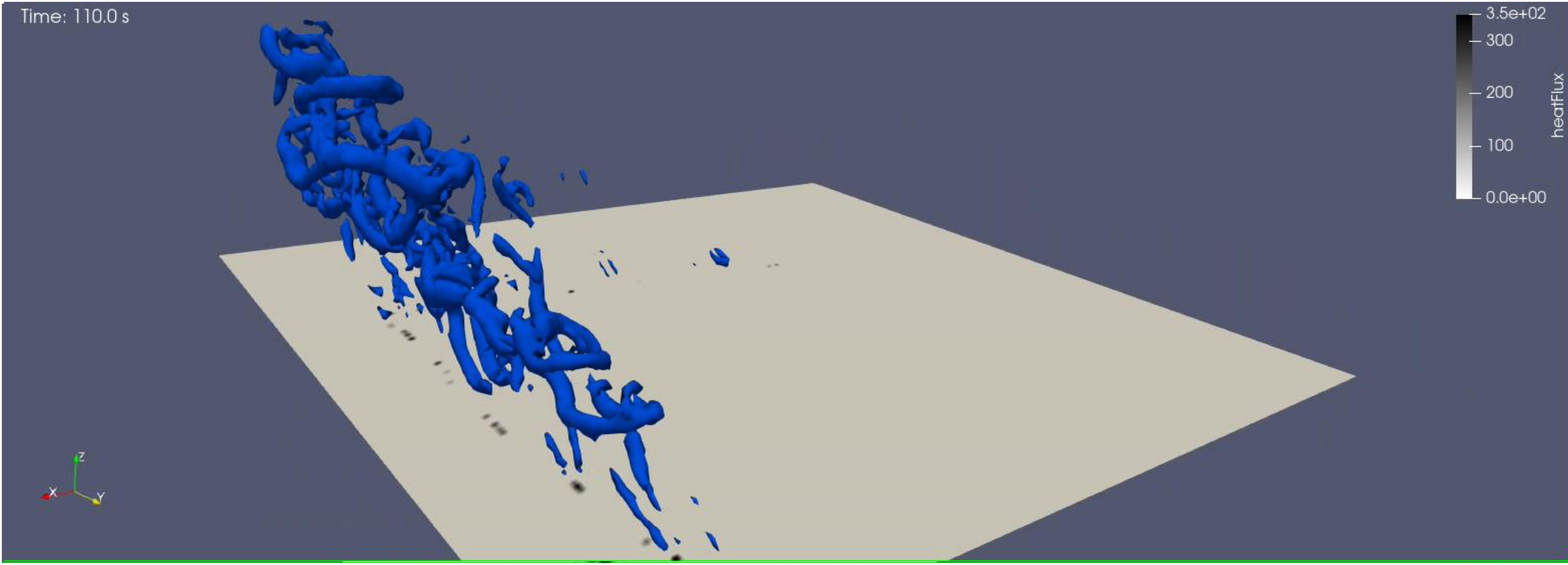
MesoNH simualtions are run at CERFACS

Animation is showing Isocontour of lambda-2 criteria (min of pressure)

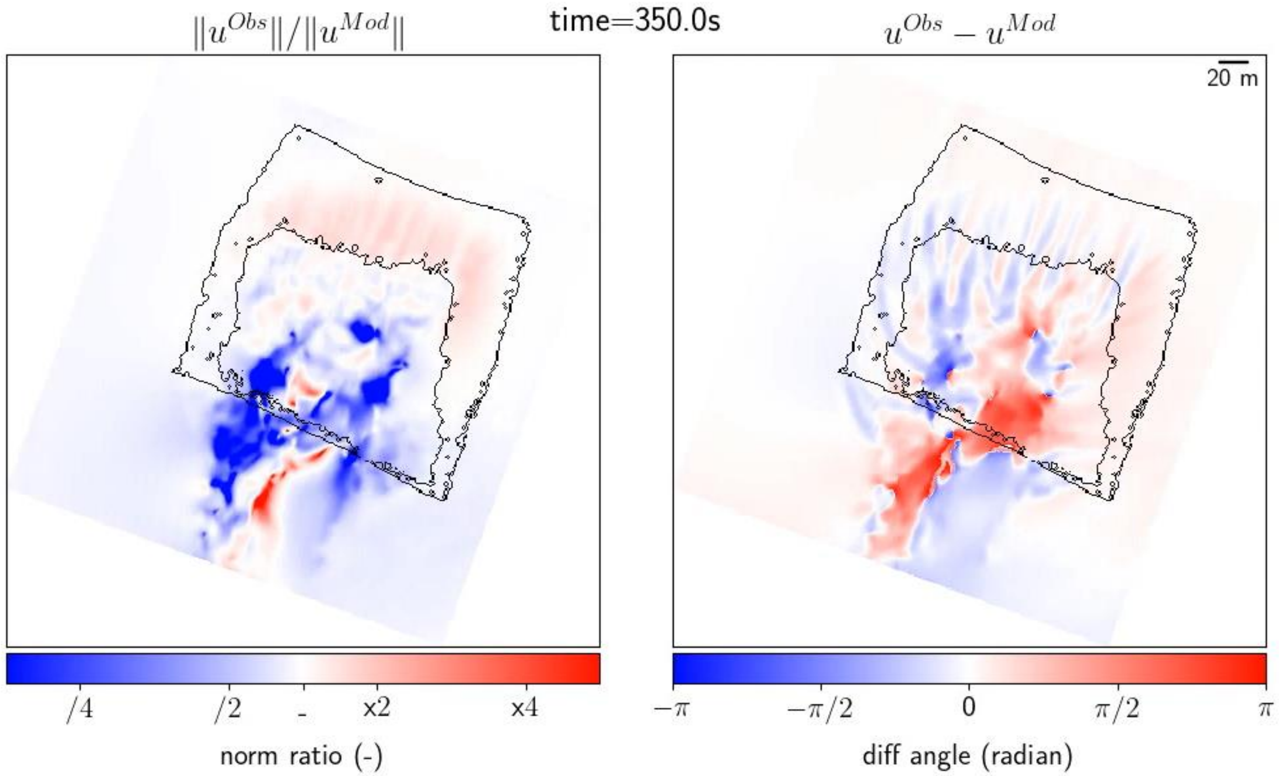
wind

★ camera start from here



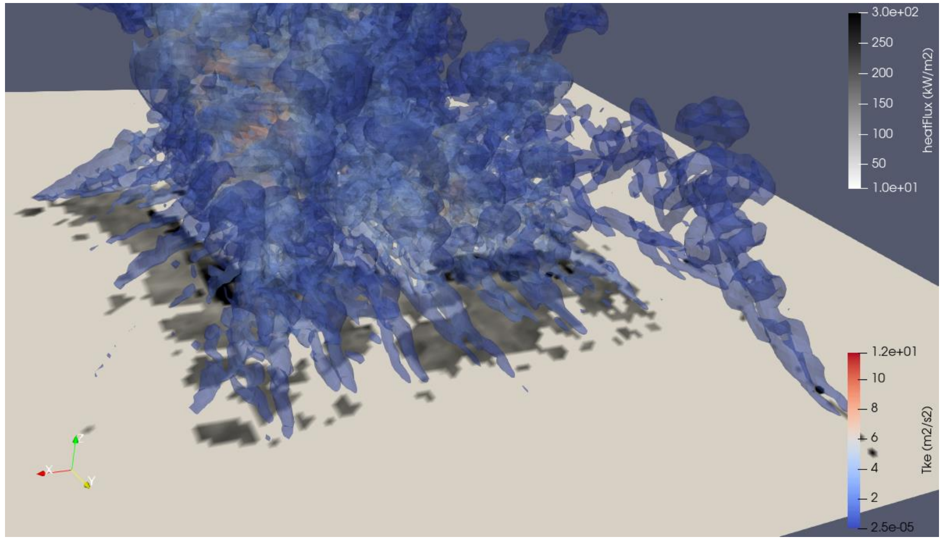


Role of the cooling area



surface wind difference between Obs and Mod simulation

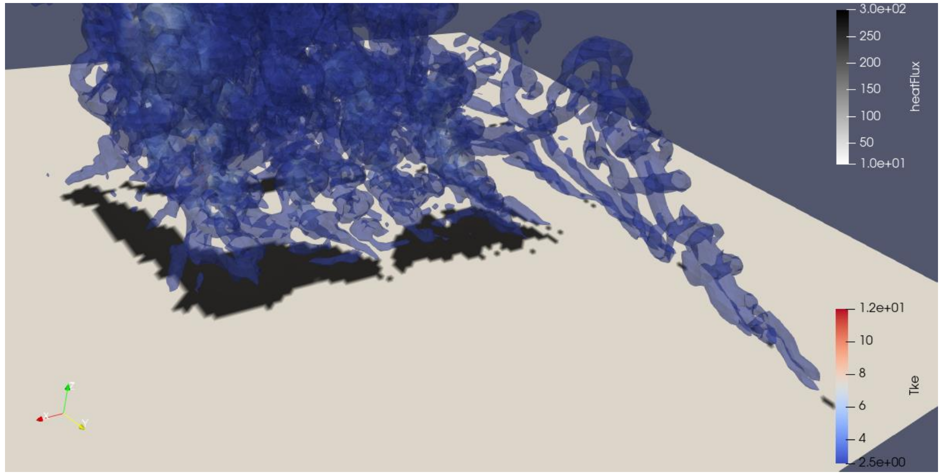
Obs: Previous simulation



Mod:

Fix nominal heat flux
Fix residence time

Same total heat release



Synthetic IR image simulation

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Motivation: End to End Simulation Strategy

biomass consumption

Raw Images (Vis, LWIR)

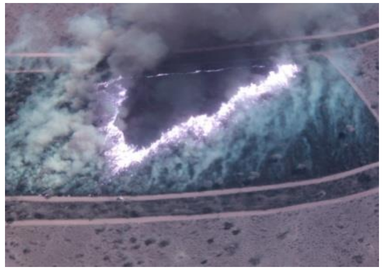


Image Processing

1. Fire behaviour
2. Energy Budget

Arrival Time, Residence Time, flame depth

f (FRP)

Simulate IR img. w/o
- Fire spread model
- MIR Radiance Obs. (only geometry)

Plume Modelling: ForeFire-MesoNH

Fire = Sensible Heat Flux

Ambient condition

LES Atmospheric Model (dx=10m)

wind

Flame & Vegetation Modelling

Fire Intensity

Empirical Relationship (flame length, temperature, soot density, fuel consumption)

FDS
Gas molar fraction
Soot volume fraction
temperature

3D Radiative Transfer Modelling: DART

aerosol density

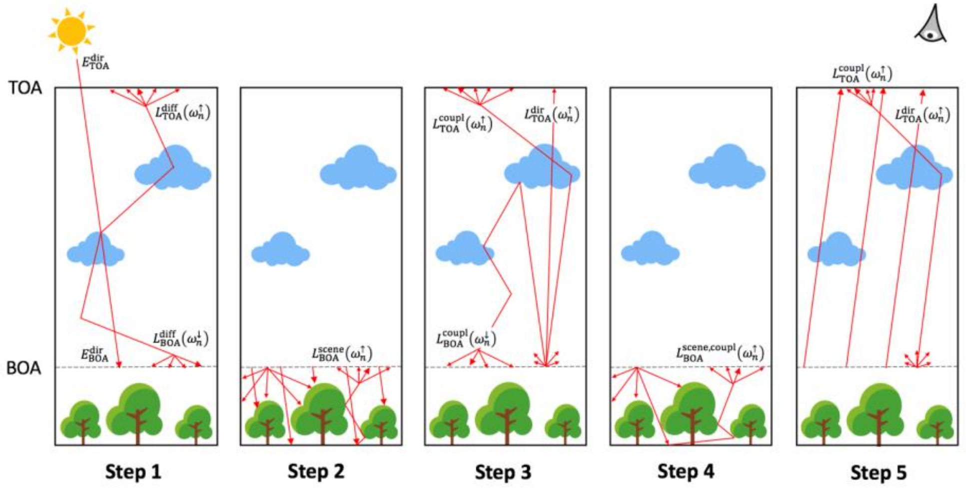
No aerosol density yet

MIR band
No scattering

3D distribution of Soot & fuel (temp. and density)

Simulated MIR images & FRP product

DART



1. Sun illumination followed by atmosphere scattering and thermal emission.
2. **Earth surface** RT.
3. **Earth-atmosphere** radiative coupling.
4. Earth surface RT of atmosphere **backscattered radiation.**
5. Transfer of BOA upward radiation to **TOA**.

forest of the RAMI IV experiment

Hot spot is a feature of the reflectance distribution of vegetation canopy

DART-FT: discrete ordinates method that iteratively tracks rays along finite discrete direction

DART-Lux: Monte Carlo sampling of paths between the light source and the detector and evaluates the contribution of these path samples. It is based on the **luxCore** engine ray tracing.

DAO tools: python application to import complex scene.

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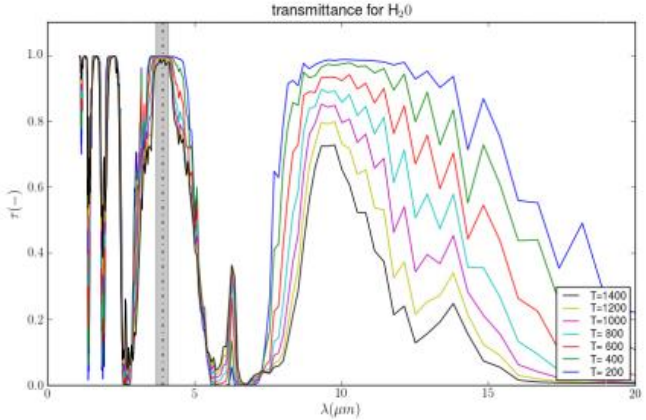
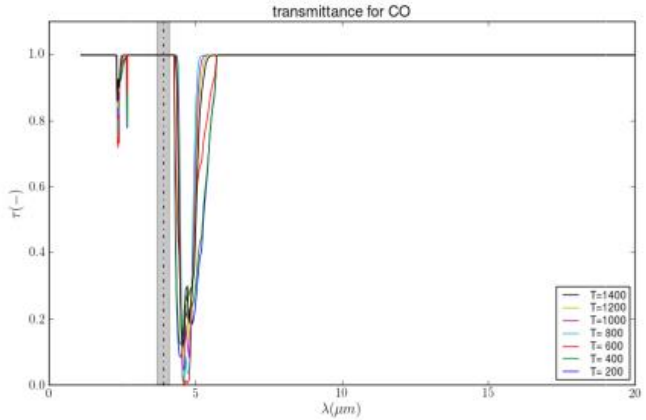
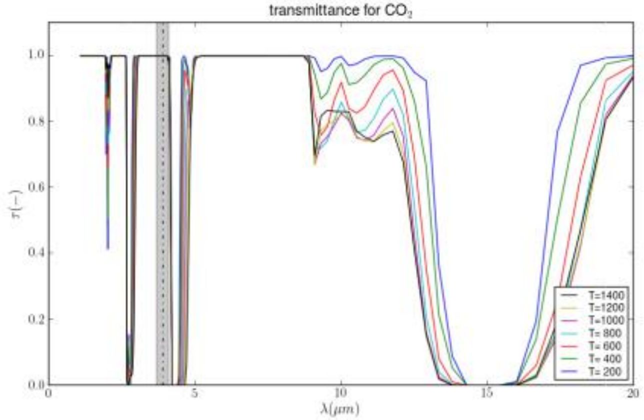
3DFireScene: absorption coefficient

Statistical Narrow Band model from EM2C







Gas absorption coefficient

Beer-Lambert $\tau = e^{-\sigma d}$ + fix distance d

4 Dimensional lookup table that depends of parameter d

$$\sigma_d\left(x_{CO_2}, x_{CO}, x_{H_2O}, T\right)[m^{-1}]$$

Soot absorption coefficient κ_s

[Bordbar et al 2020]

ν_s soot volume fraction

η wave number

$$\kappa_s = \alpha_\eta \nu_s \eta \quad (1)$$

$$n_s = 1.811 + 0.1263 ln(\lambda) + 0.027 ln^2(\lambda) + 0.0417 ln^3(\lambda) \quad (2)$$

$$k_s = 0.5821 + 0.1213 ln(\lambda) + 0.2309 ln^2(\lambda) - 0.01 ln^3(\lambda) \quad (3)$$

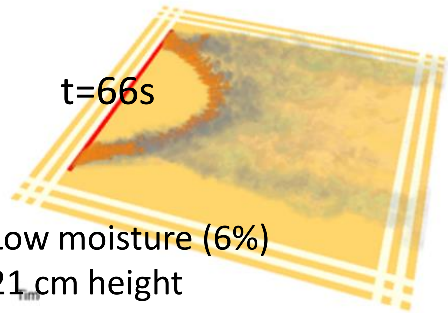
complex index of refraction o soot

$$\alpha_\eta = \frac{36\pi n_s k_s}{\left(n_s^2 - k_s^2 + 2\right)^2 + 4\pi n_s^2 k_s^2} \quad (4)$$

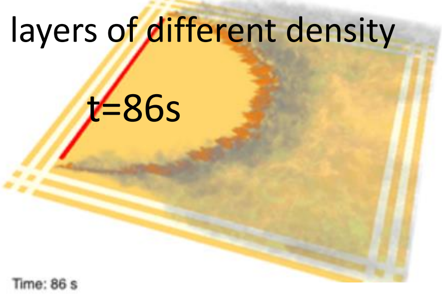
Fire Field Exp. Monitoring & Plume Simulation – R. Paugam

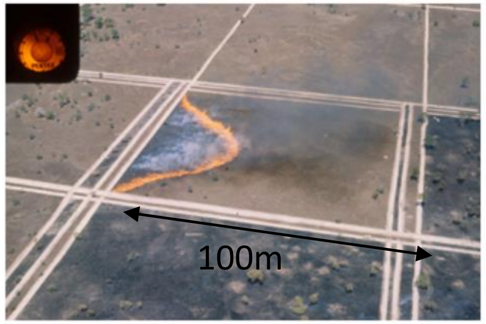
Medium Scale Fire - FDS

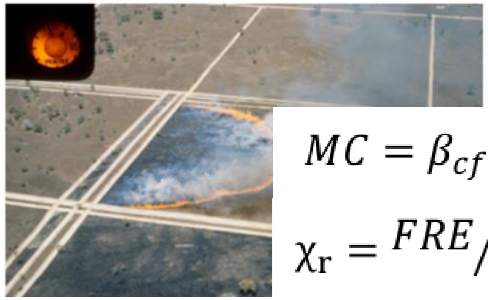
1 ha plot of grass



Low moisture (6%)
21 cm height
0.25x0.125 cm resolution
2 layers of different density







DART Lux: 1 band 1 sensor
Degraded resolution x2

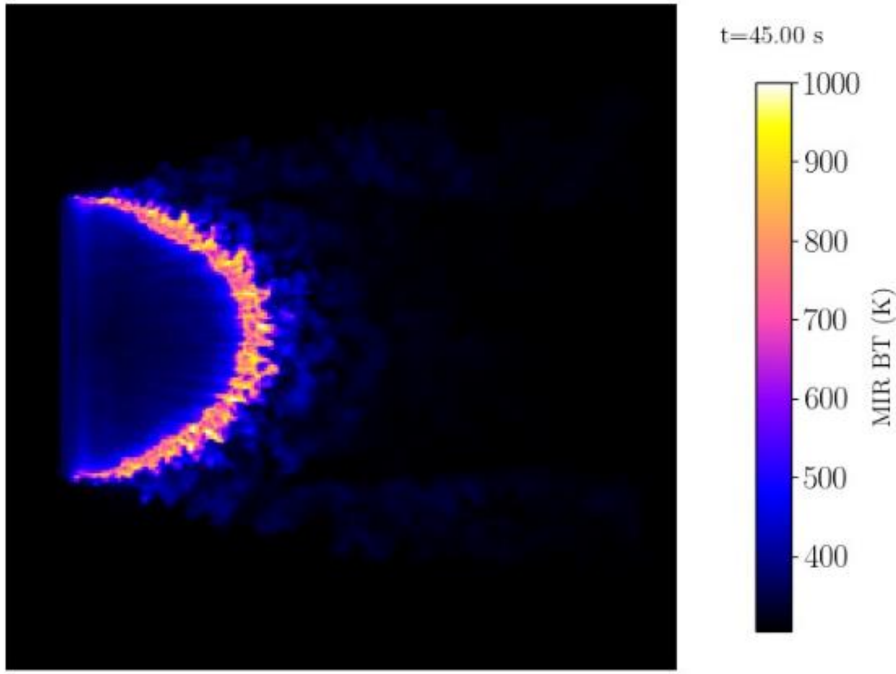
```
At 50s:
29207 plots with vegetation.
29300 plots with char.
0 plots with ash.
2458 plots with gas or soot.
0 plots in the plume.
```

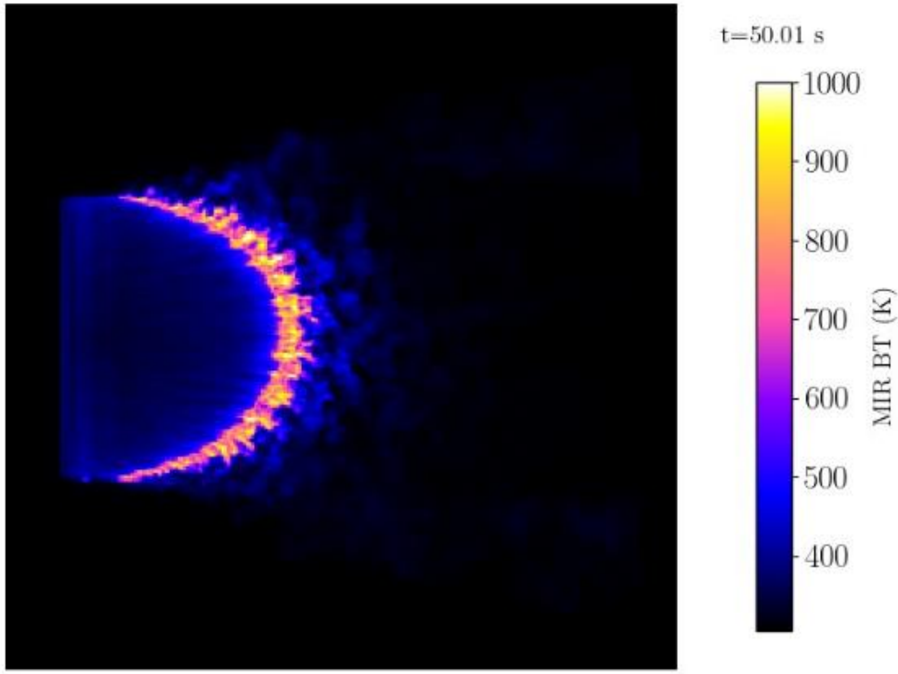
1 scene: 15 min 4GB Mem

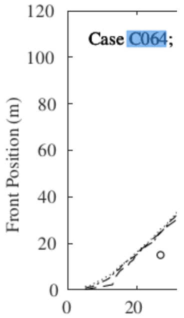
$$MC = \beta_{cf}\, FRE$$

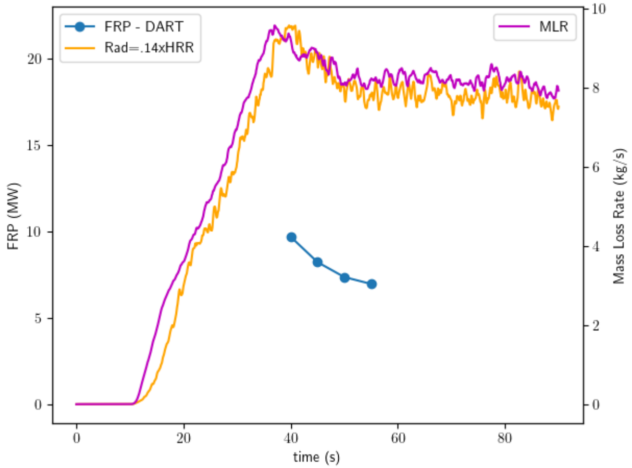
$$\chi_r = FRE/_{H\ MC} = 1/_{H\ \beta_{cf}} \approx 0.14$$

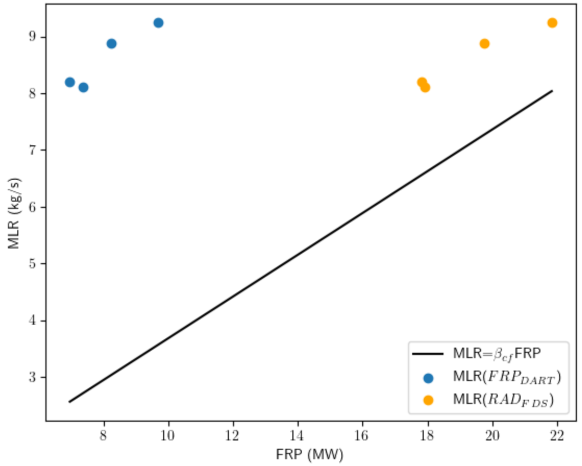
pinhole camera 200 m above the plot center











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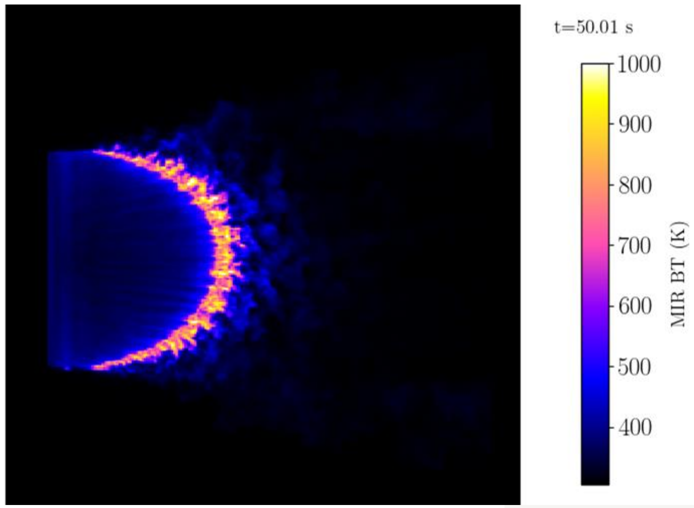
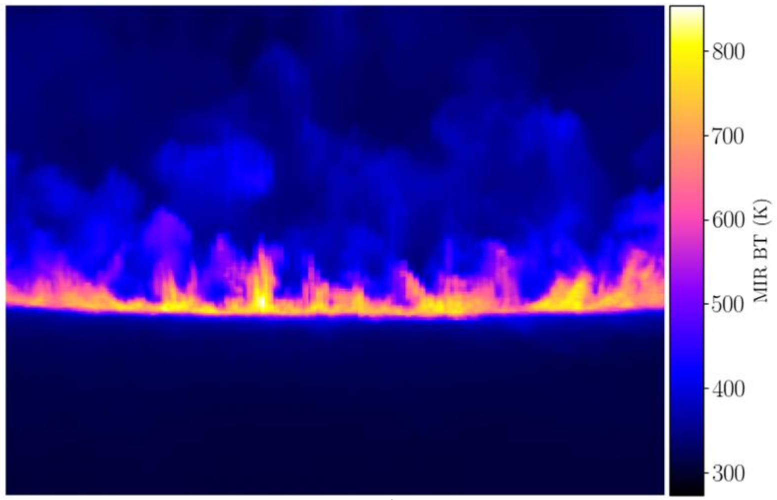
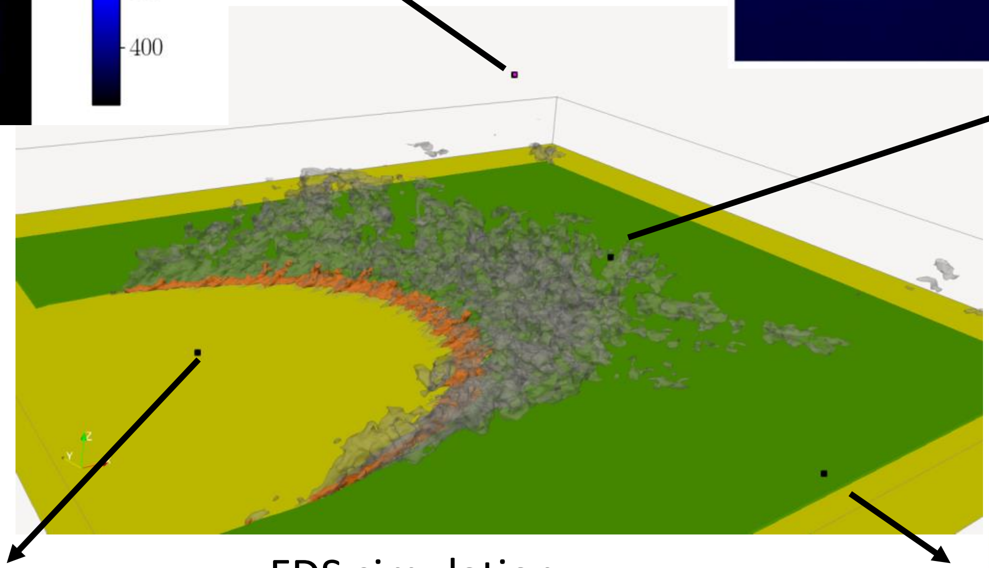
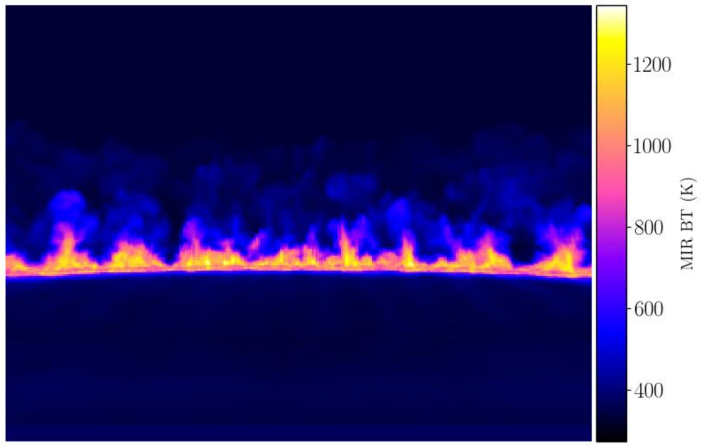
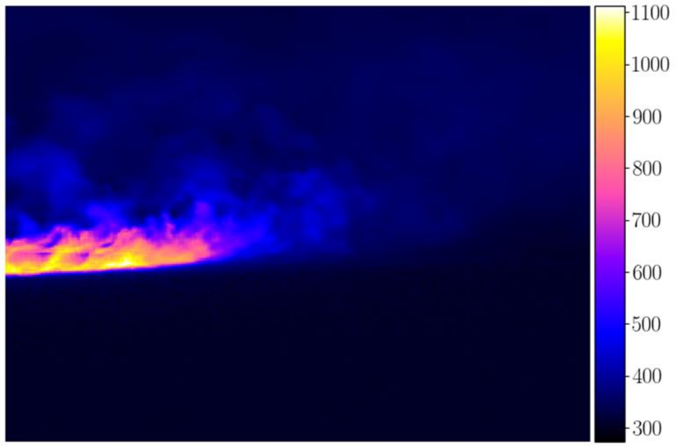
Medium Scale Fire – flame geometry effect





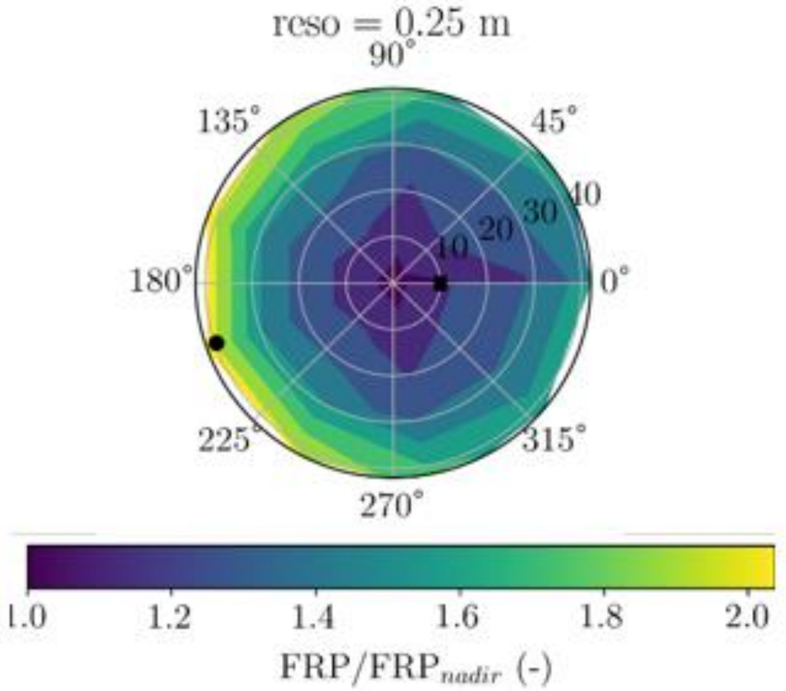


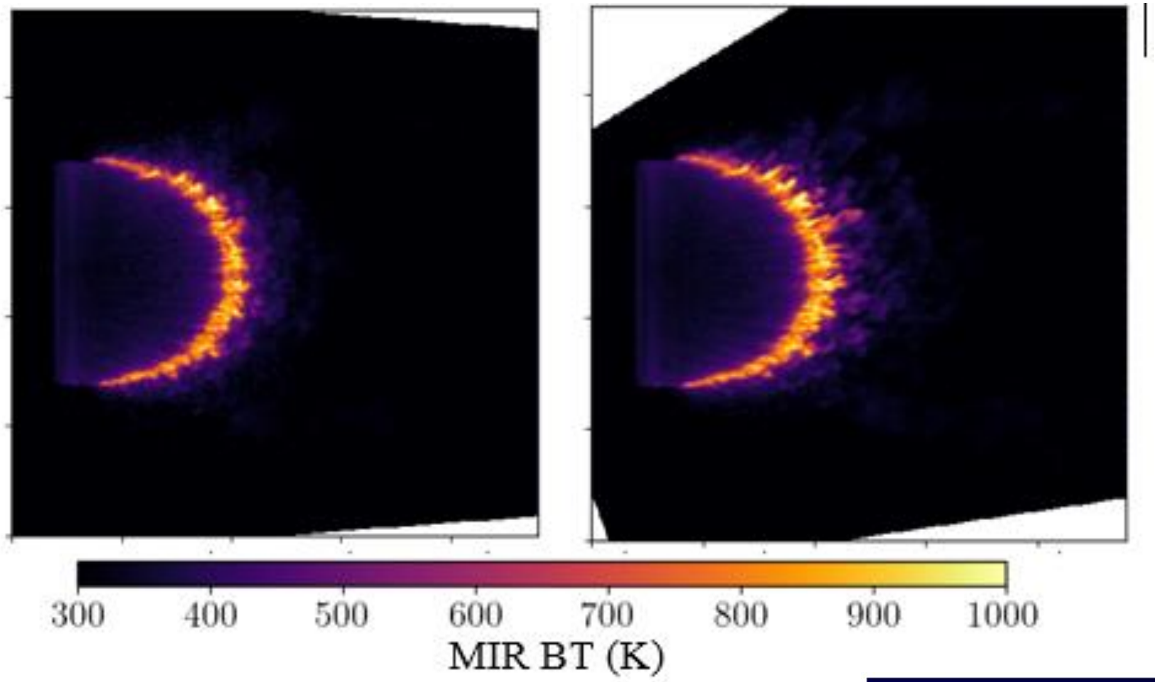


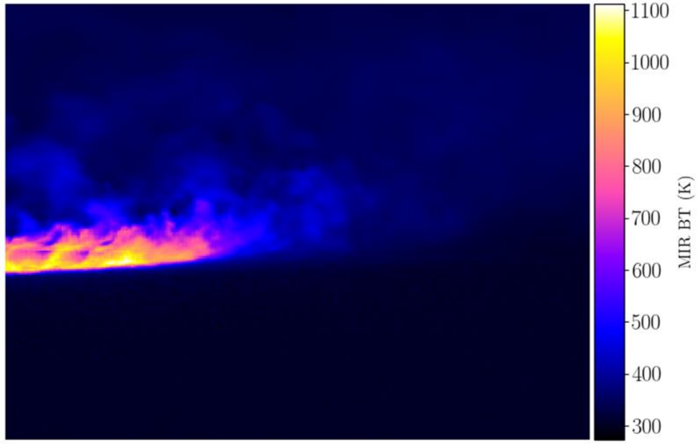


FDS simulation
green: grass
orange: Heat Release Rate per Volume
grey: soot volume fraction
black point: camera location

Medium Scale Fire – flame geometry effect







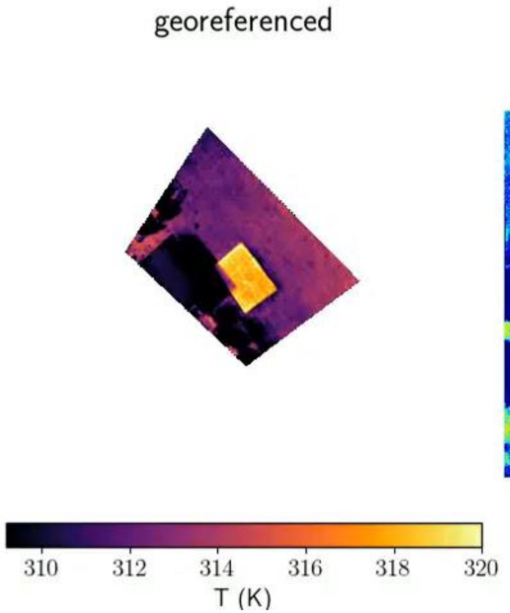
Effect of flame on FRP calculation

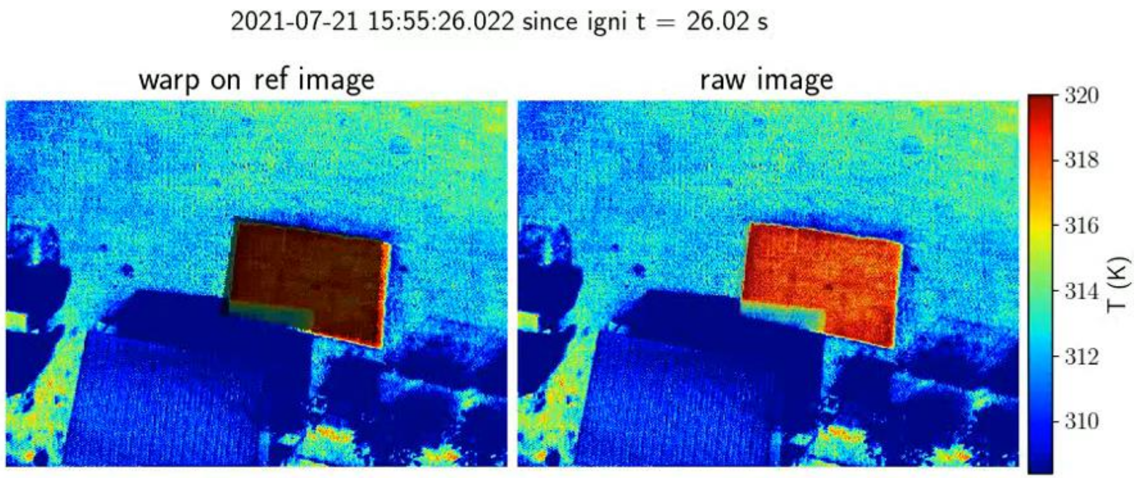
Conclusion

- **Map Fire Behavior** metrics at high resolution
- **Model high resolution wind** field induced by observed fire behavior
- Strong impact of the cooling area on the wind field
- Model FRP from FDS scene using DART (still in progress)
- Potential impact of flame geometry on FRP

Next:

- More detailed analysis of the wind field and ROS field
- Data set of ROS, wind and fuel load (here from FRE)
- Collecting more data using UAV and an optris P640 piloted with a raspberry (30Hz frame rate).





Thanks

You can see more on the work of the 3DFirelab project at

3dfirelab.eu

Acknowledgments

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MARIE CURIE ACTIONS

European Commission

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