

Simple models for wildfire plumes

Martin Janssens



Not detailed models for actual wildfire plumes!

Martin Janssens



Goals for this morning:

Make a conceptual model for this plume to determine:

1. How high will this plume reach?
2. Will it condensate?

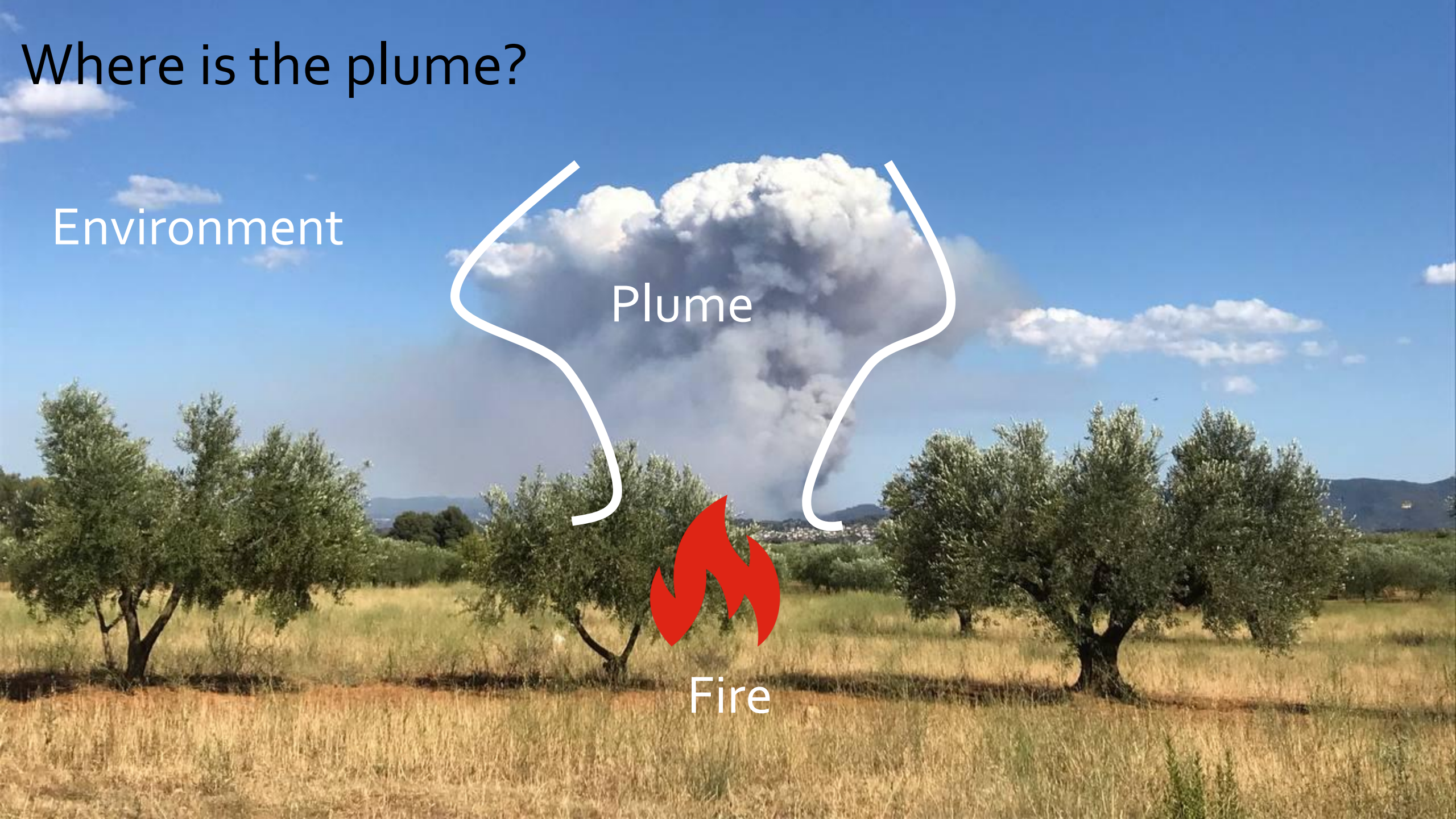


Where is the plume?

Environment

Plume

Fire



What do we need to know, to predict the plume's top?

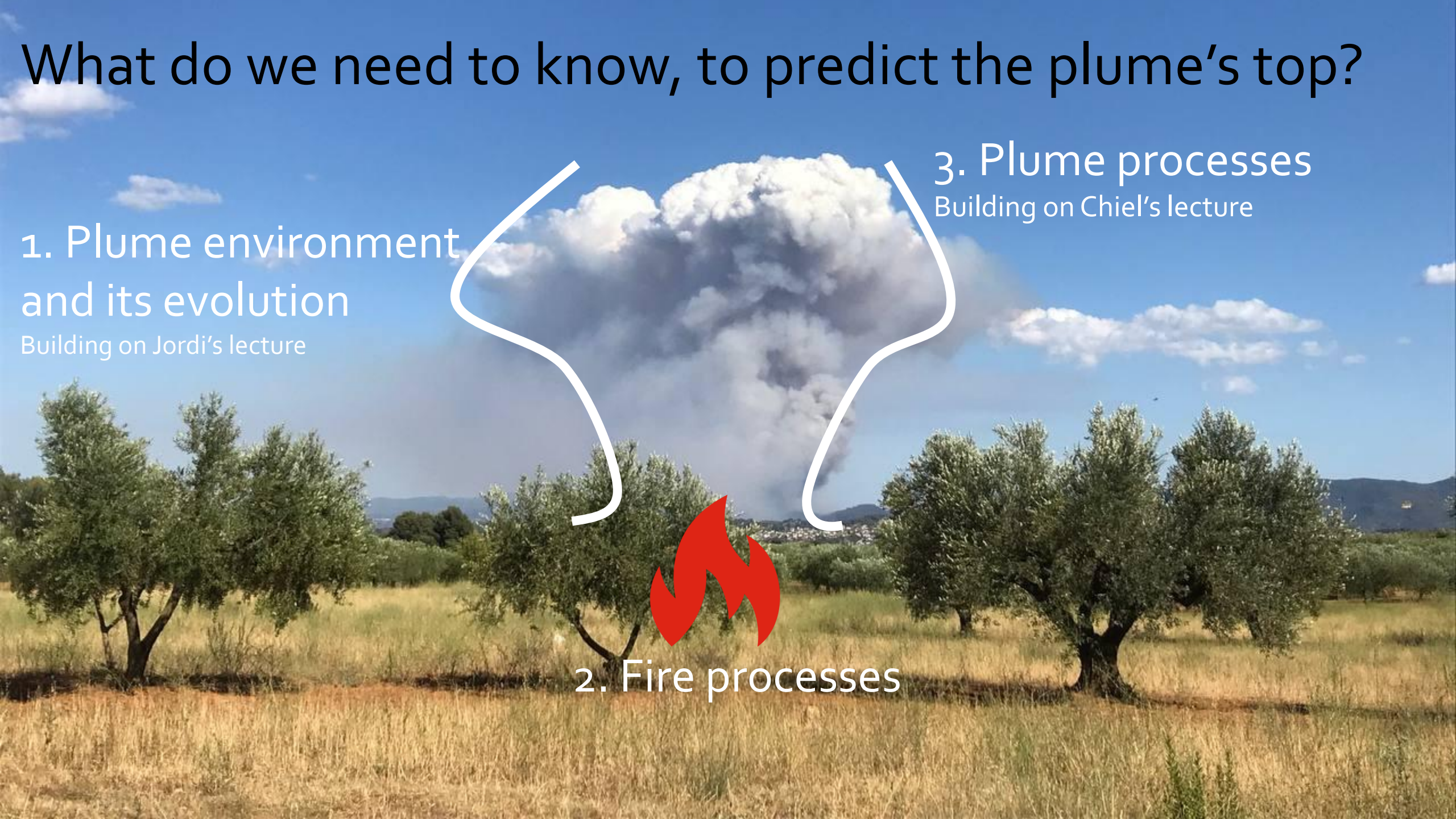
1. Plume environment and its evolution

Building on Jordi's lecture

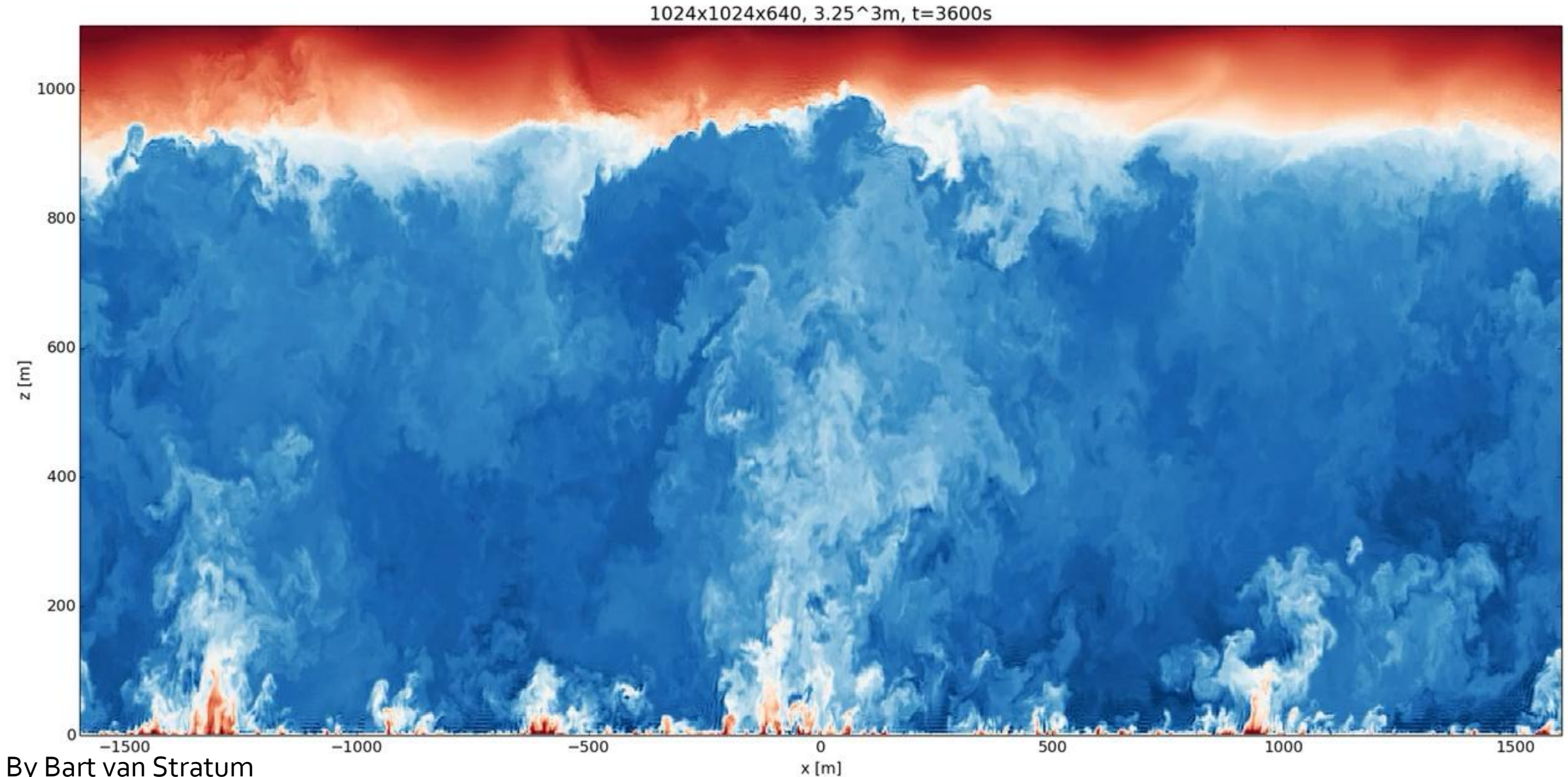
3. Plume processes

Building on Chiel's lecture

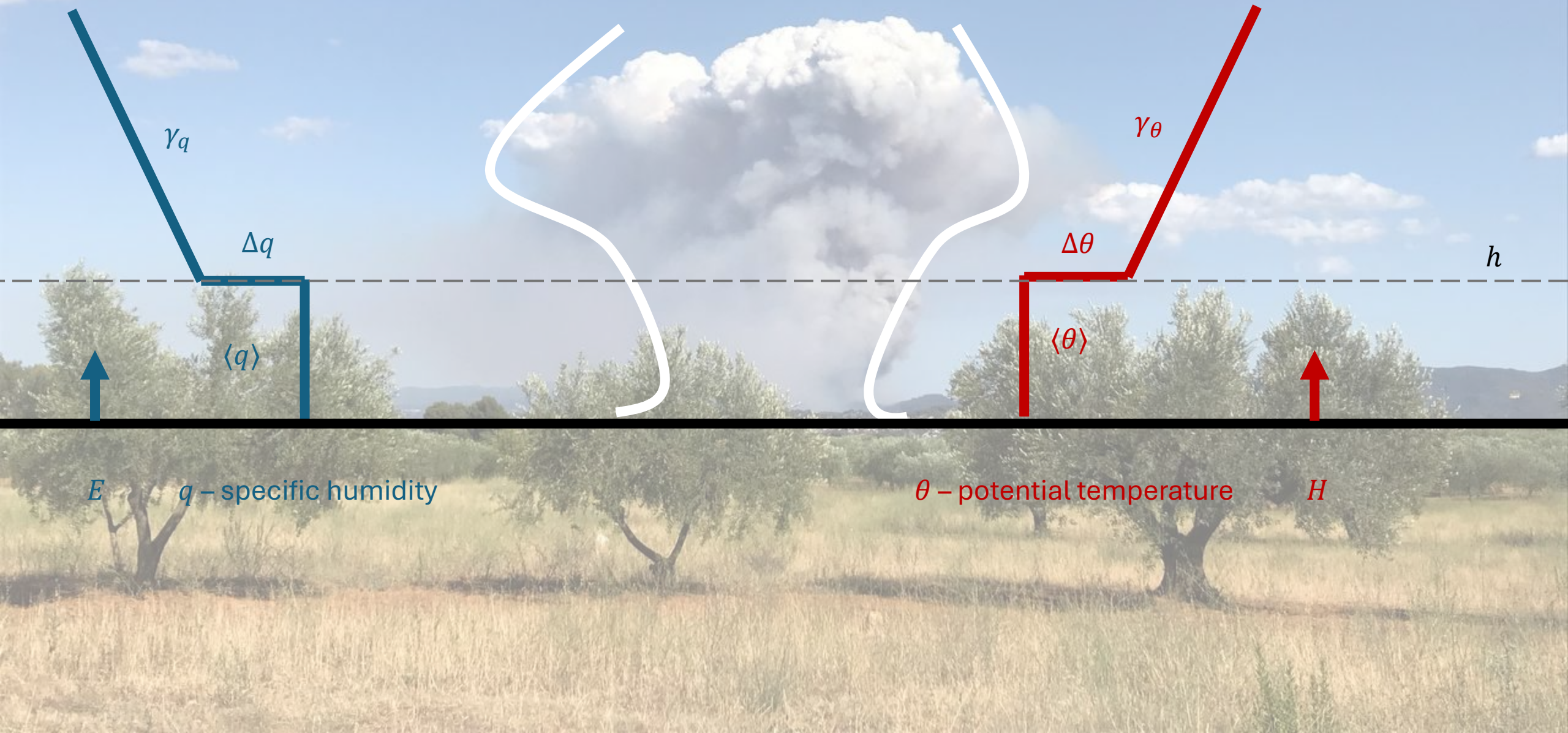
2. Fire processes



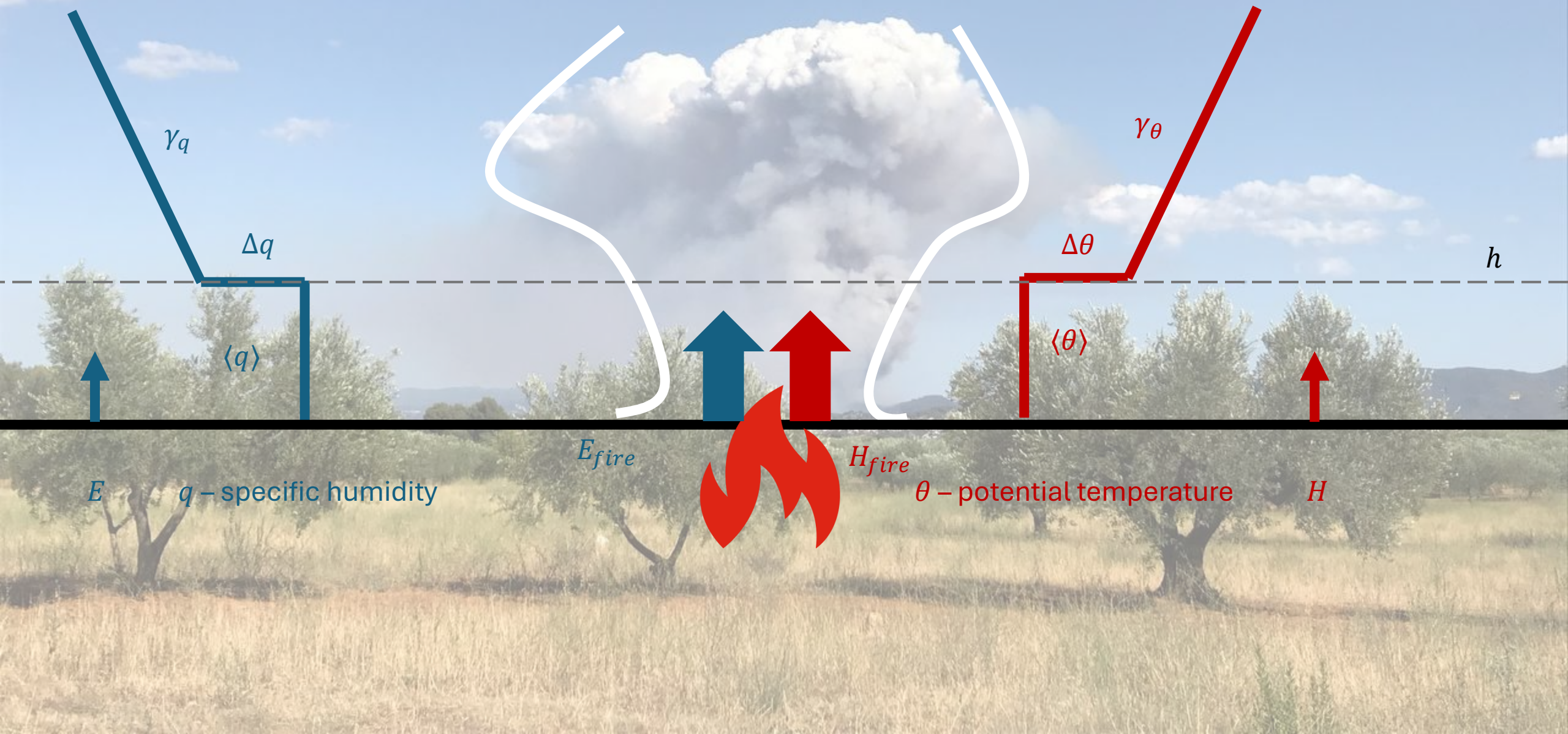
1. The environment – the daytime convective BL



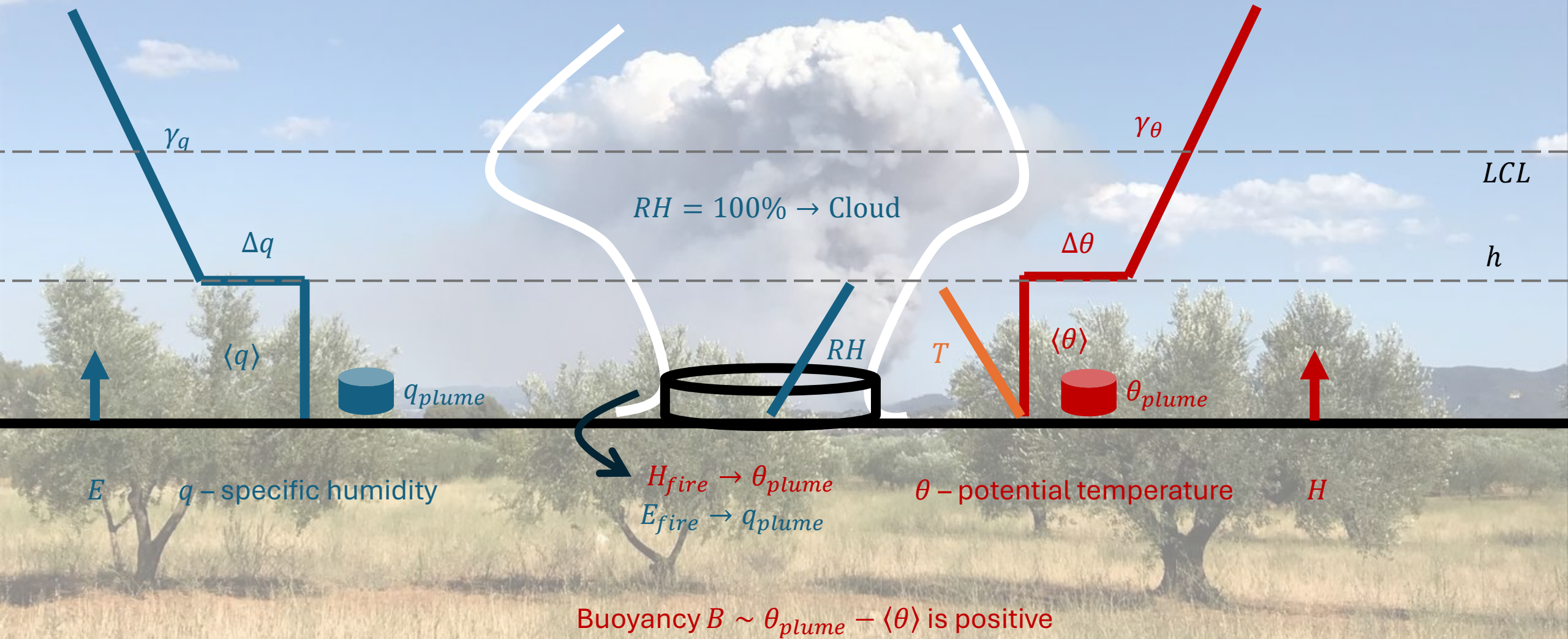
1. The environment – the daytime convective BL



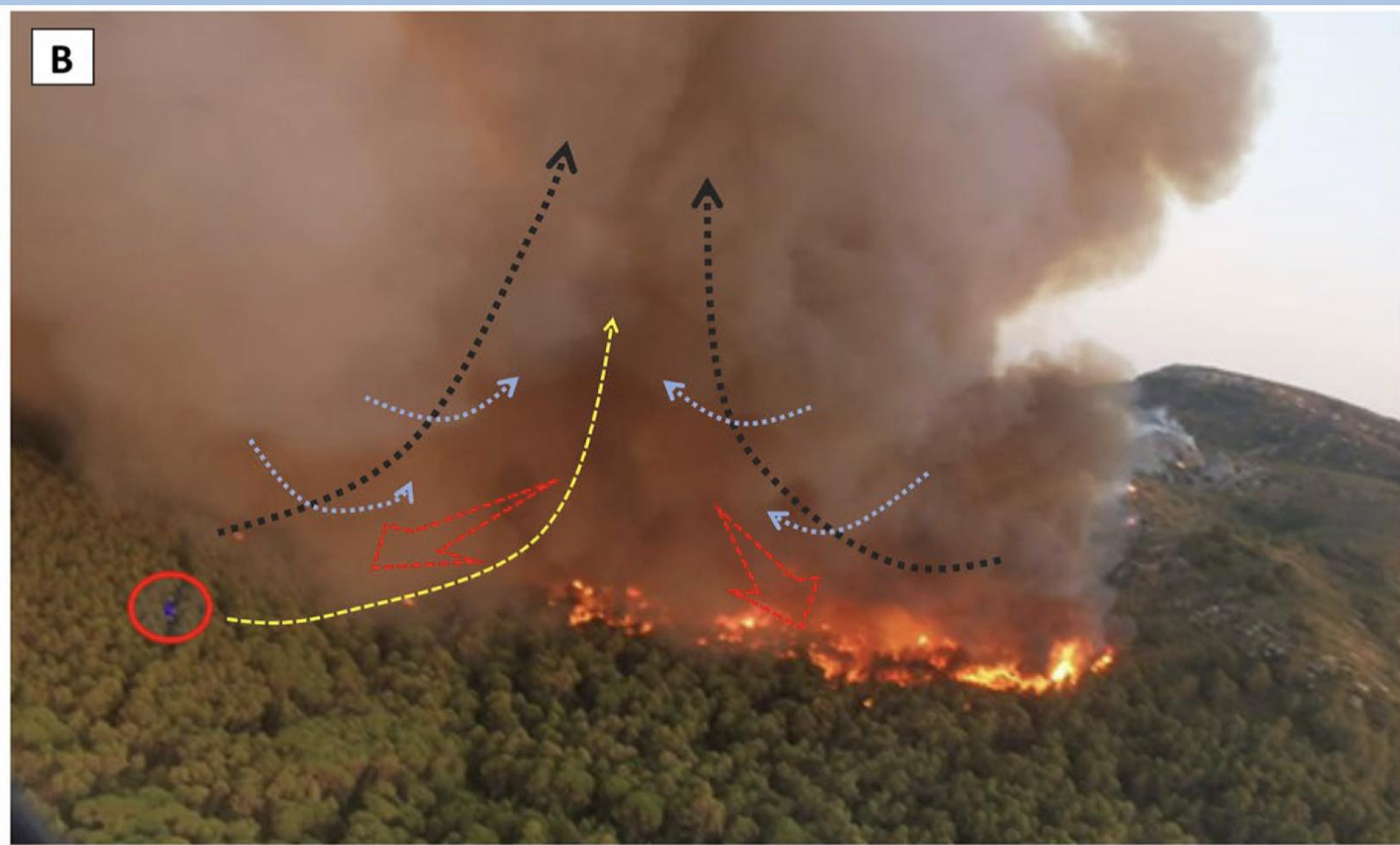
2. The fire – a heat and moisture source



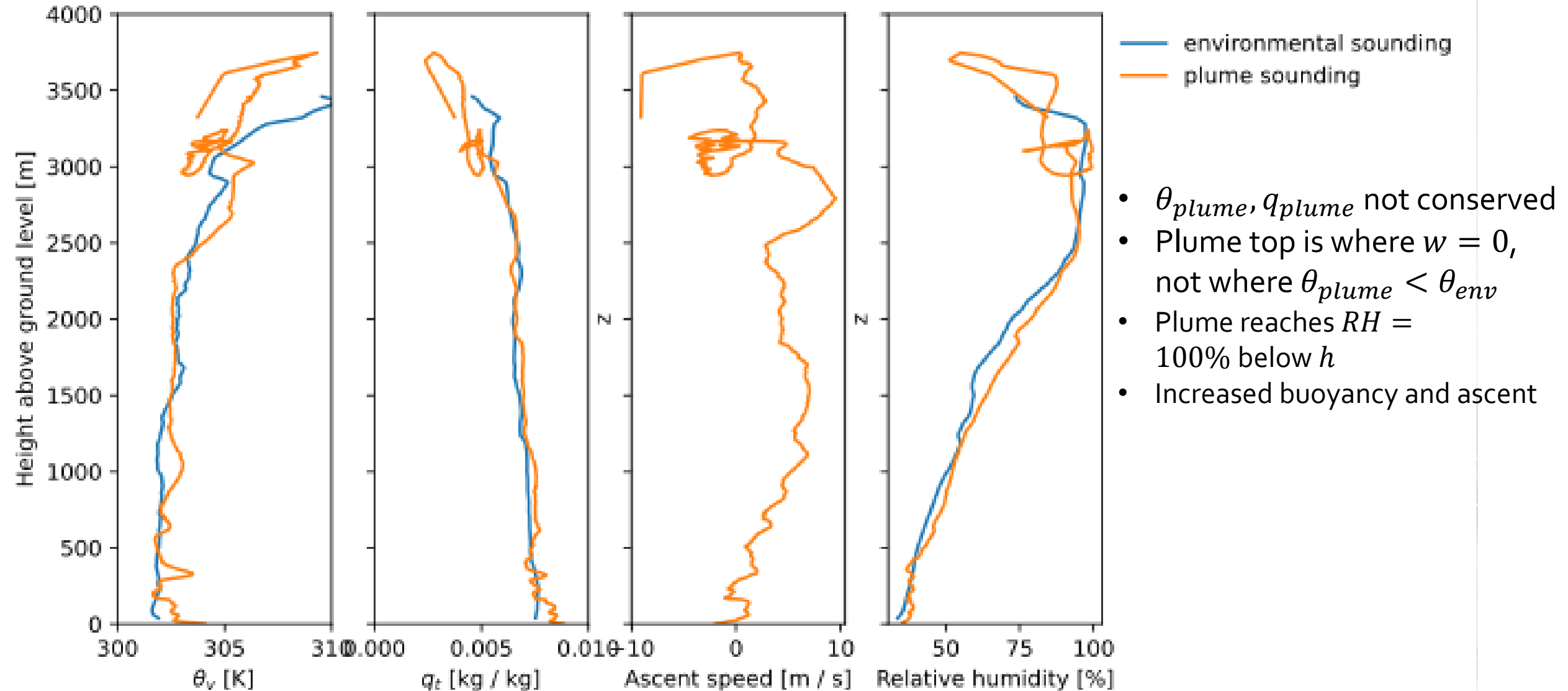
3. Plume processes – the rising parcel



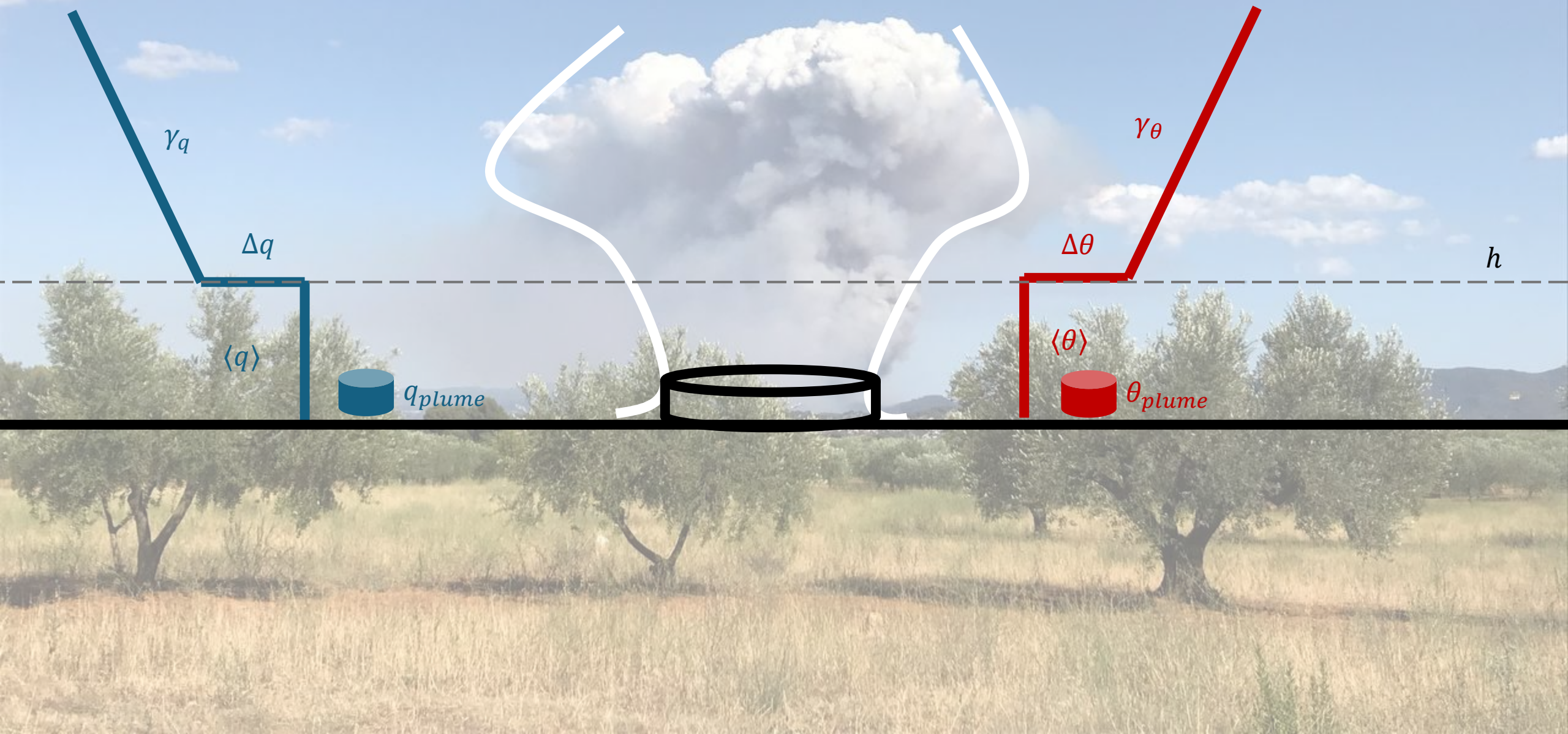
3. Plume processes – how does this compare with reality?



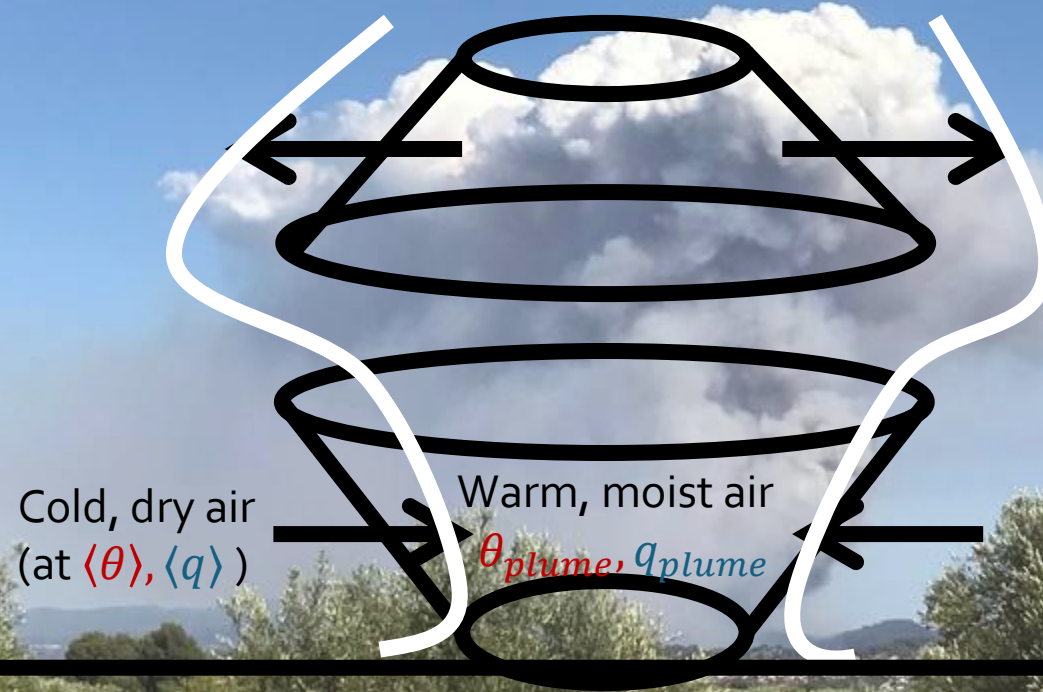
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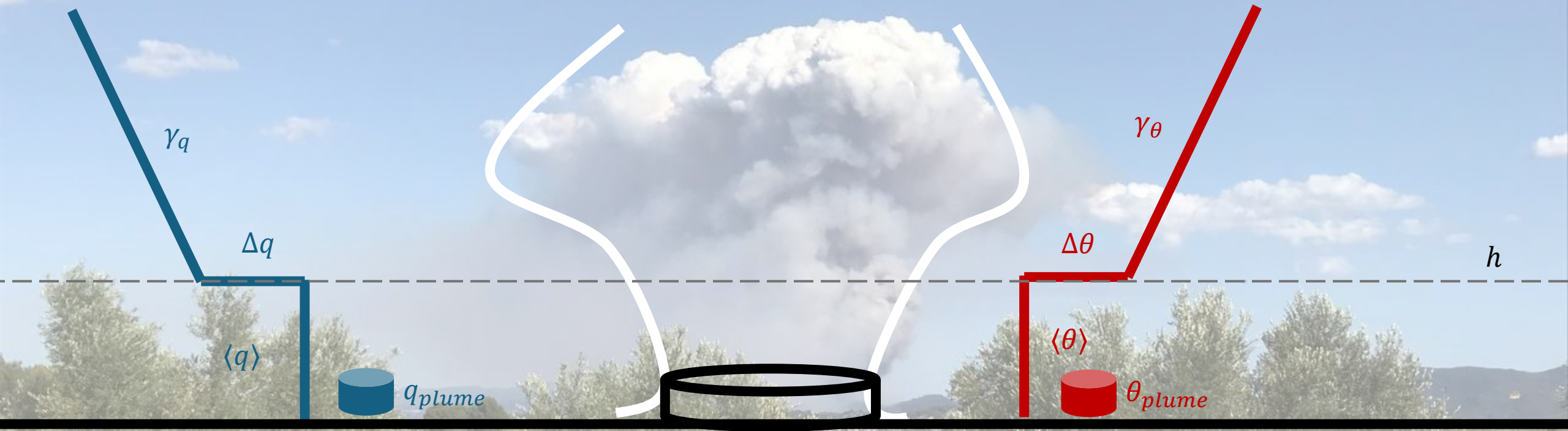
3. Plume processes – an *entraining* parcel



3. Plume processes – an *entraining* parcel



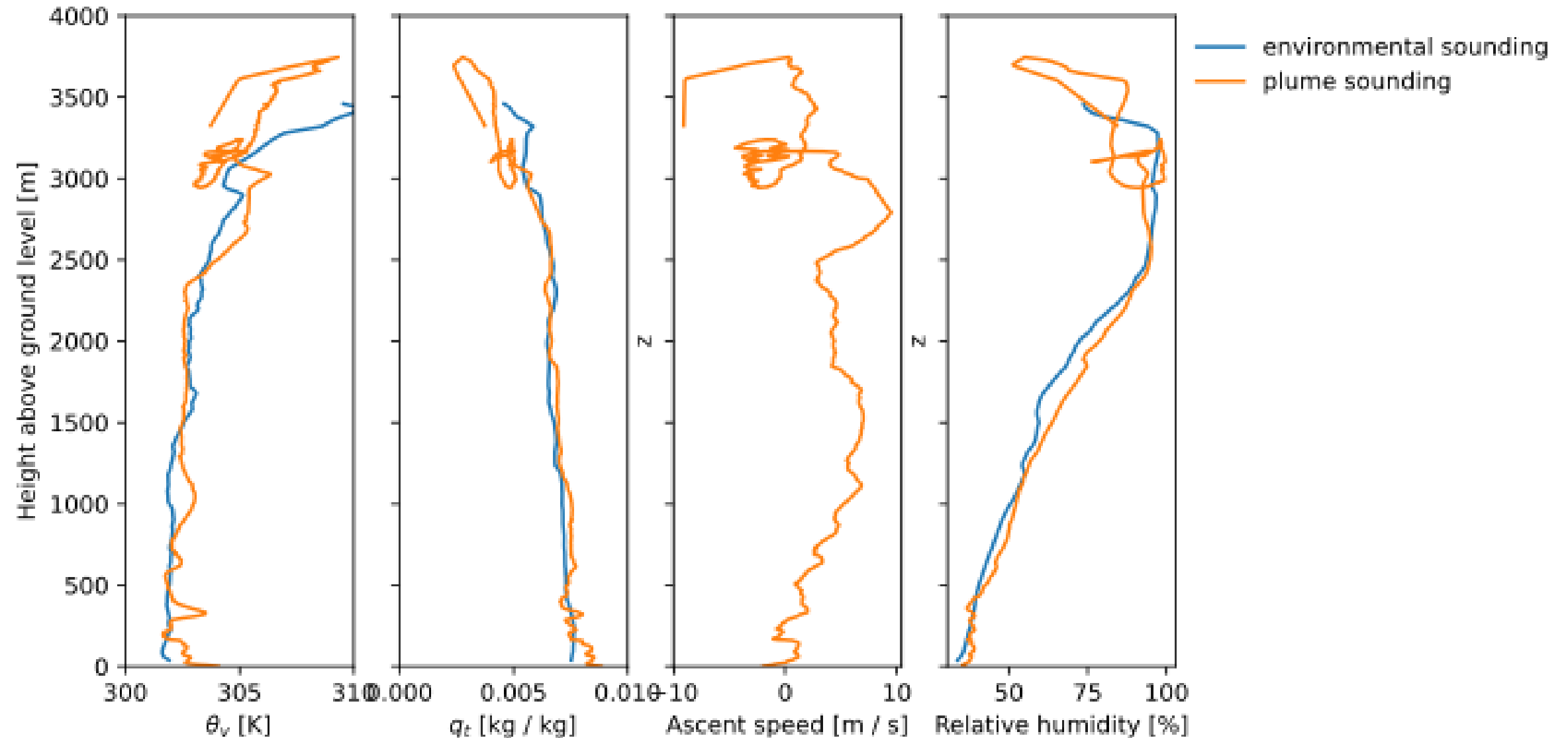
3. Plume processes – an *entraining* parcel



Entrainment

1. Grows the plume
2. Mixes the plume properties towards the environment

3. Plume processes – how does this compare with reality?



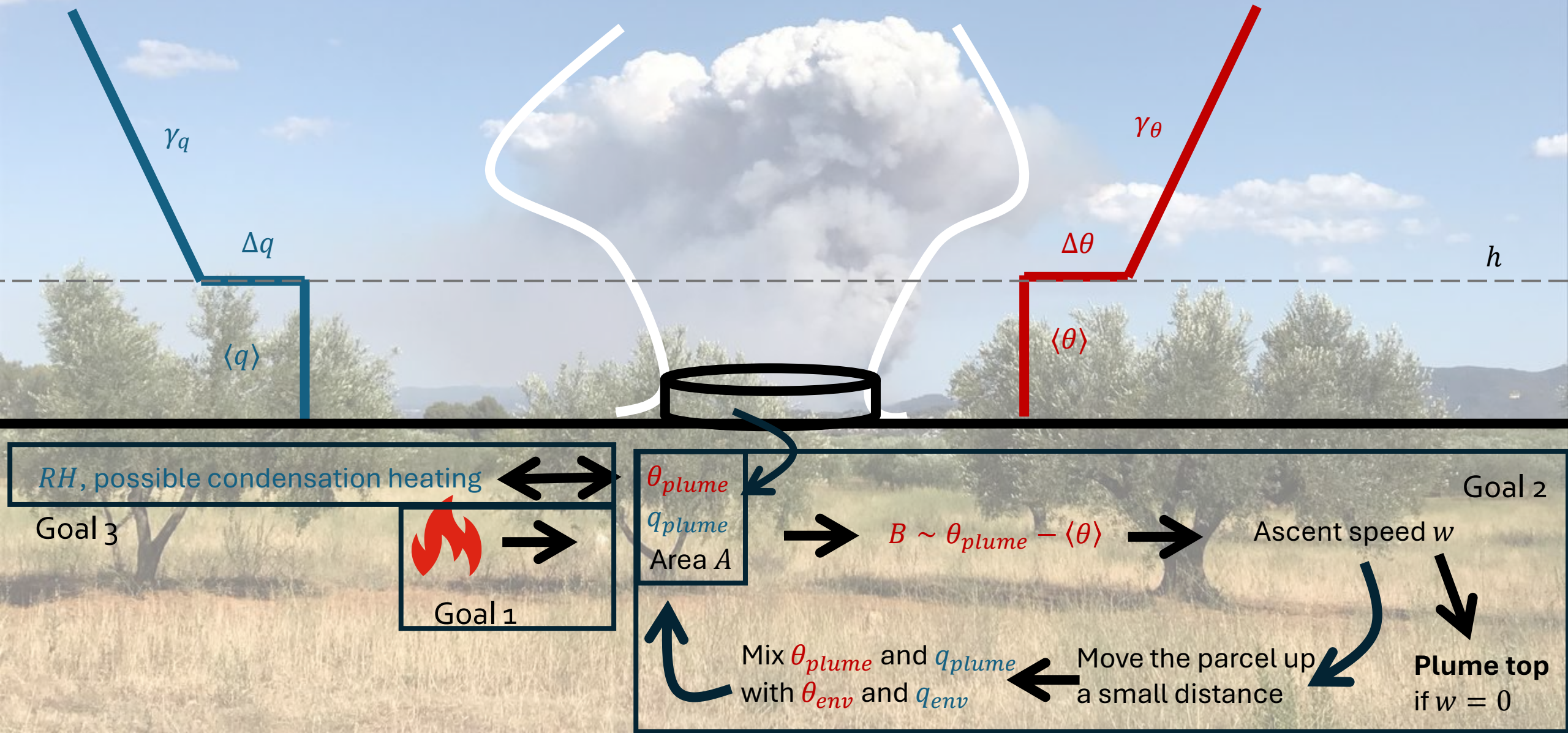
3. Plume processes – how much to mix?



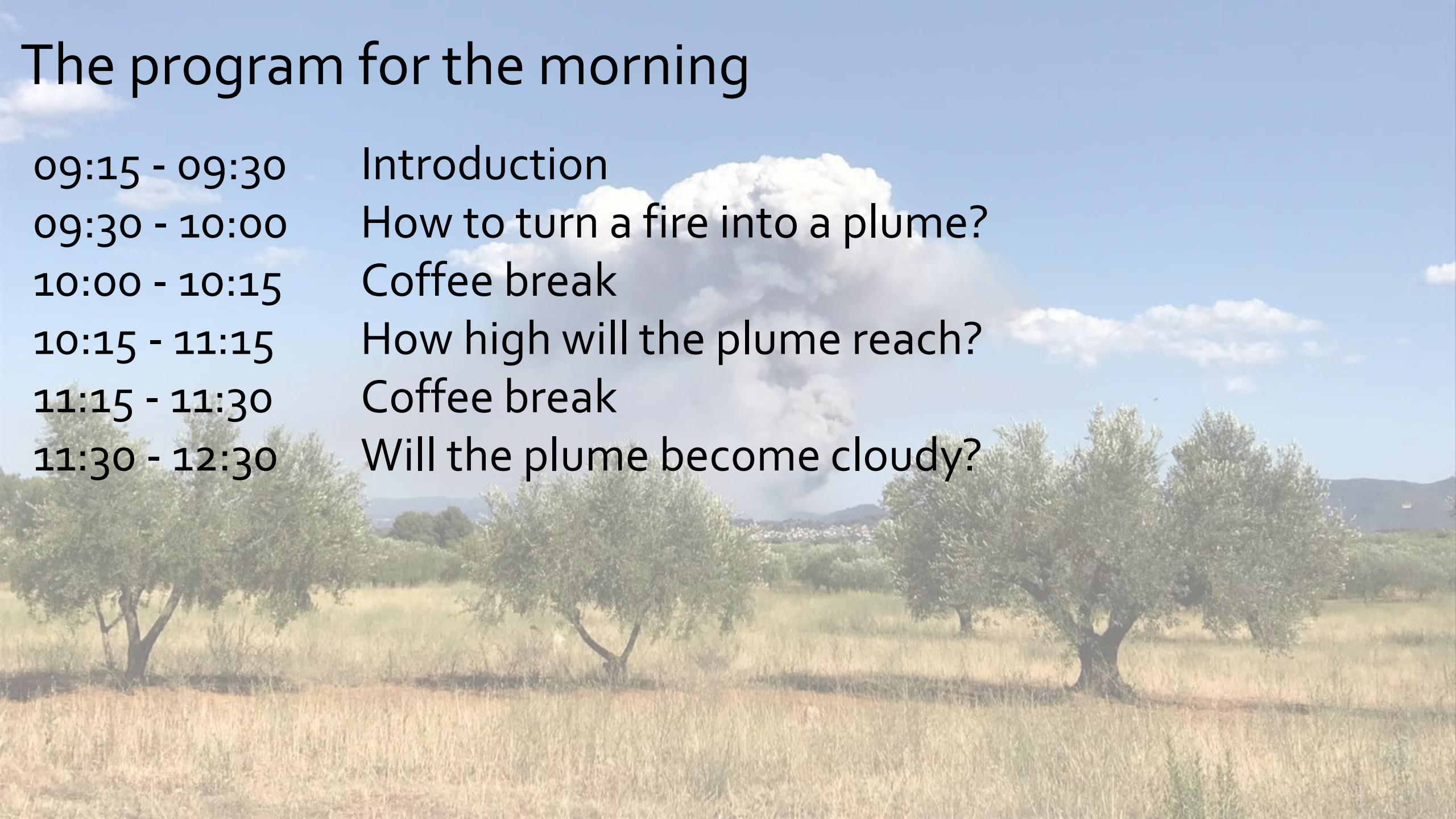
We assume:

1. The bigger the difference $\theta_{plume} - \langle \theta \rangle$, the more quickly θ_{plume} will reduce towards $\langle \theta \rangle$ (and the same for moisture)
2. Bigger plumes mix less efficiently, because their core is “protected”

An idealised plume: A summary

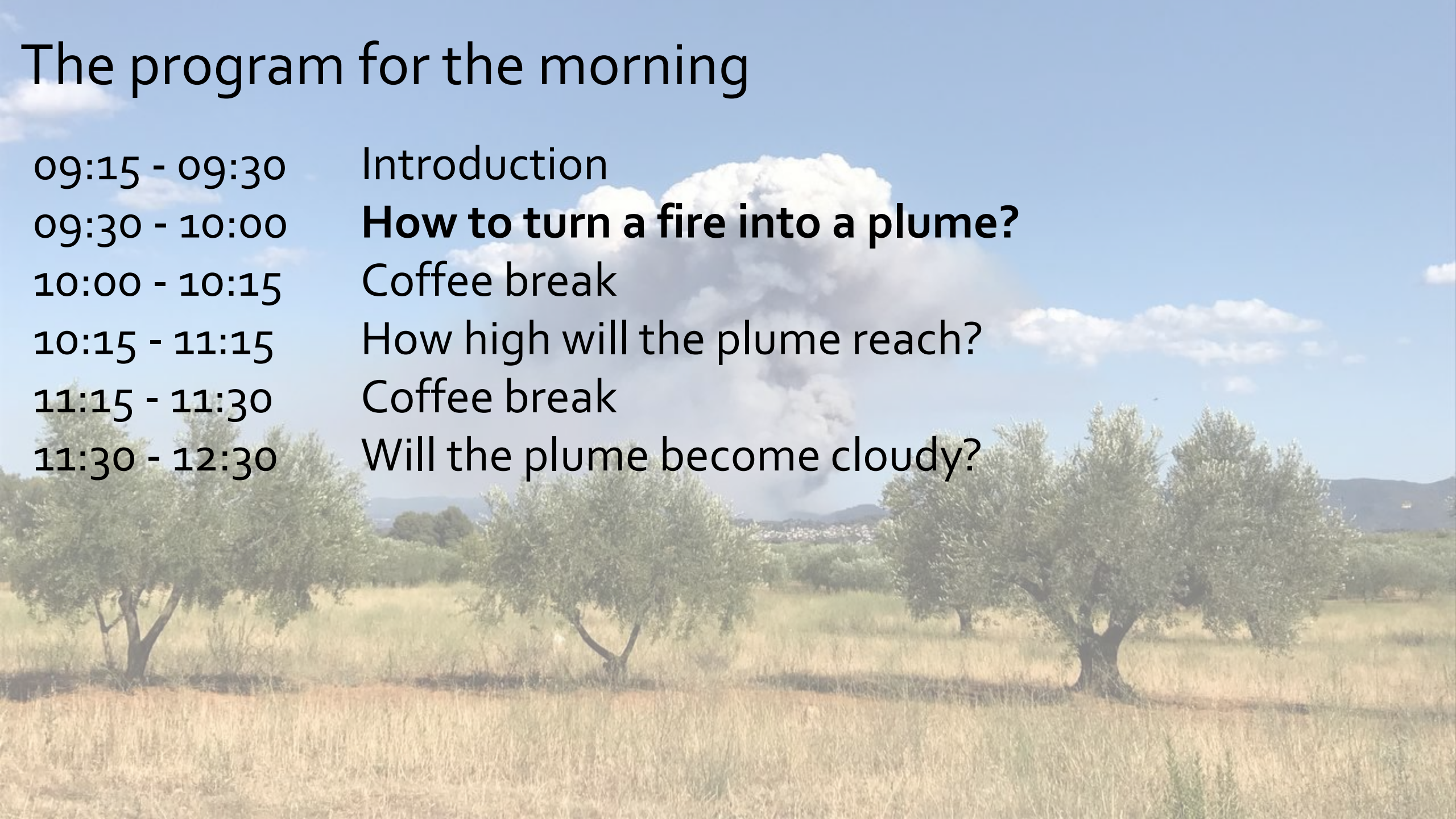


The program for the morning



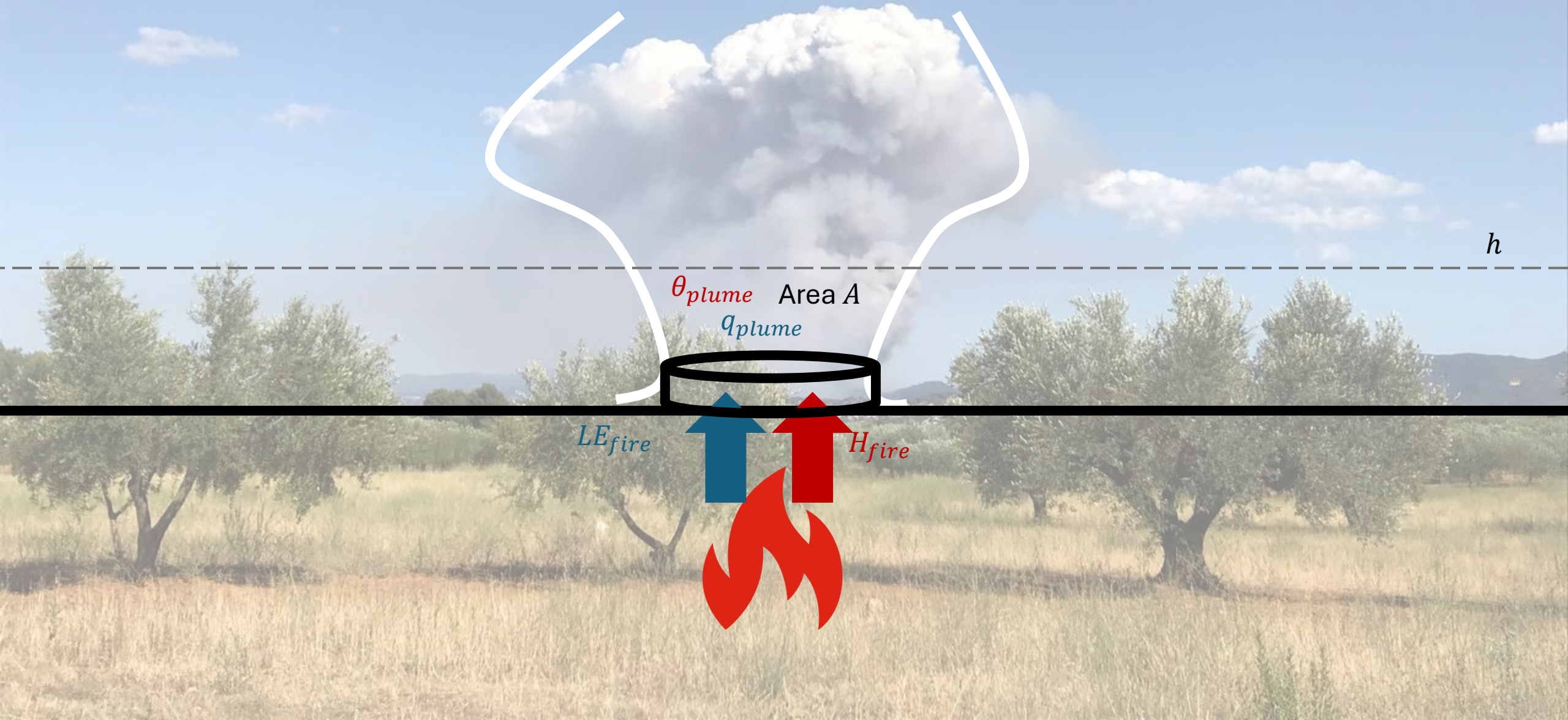
09:15 - 09:30	Introduction
09:30 - 10:00	How to turn a fire into a plume?
10:00 - 10:15	Coffee break
10:15 - 11:15	How high will the plume reach?
11:15 - 11:30	Coffee break
11:30 - 12:30	Will the plume become cloudy?

The program for the morning

The background of the slide is a photograph of a landscape. In the foreground, there is a field of dry, yellowish-brown grass. Several olive trees with green foliage are scattered across the middle ground. In the far background, a large, dark, billowing plume of smoke or ash rises into a clear blue sky, suggesting a volcanic eruption. The overall scene is bright and sunny.

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How to turn a fire into a plume?



Exercise 1: Construct the fire-to-surface parcel model

<https://wildfiredataportal.eu/science/modeling/>

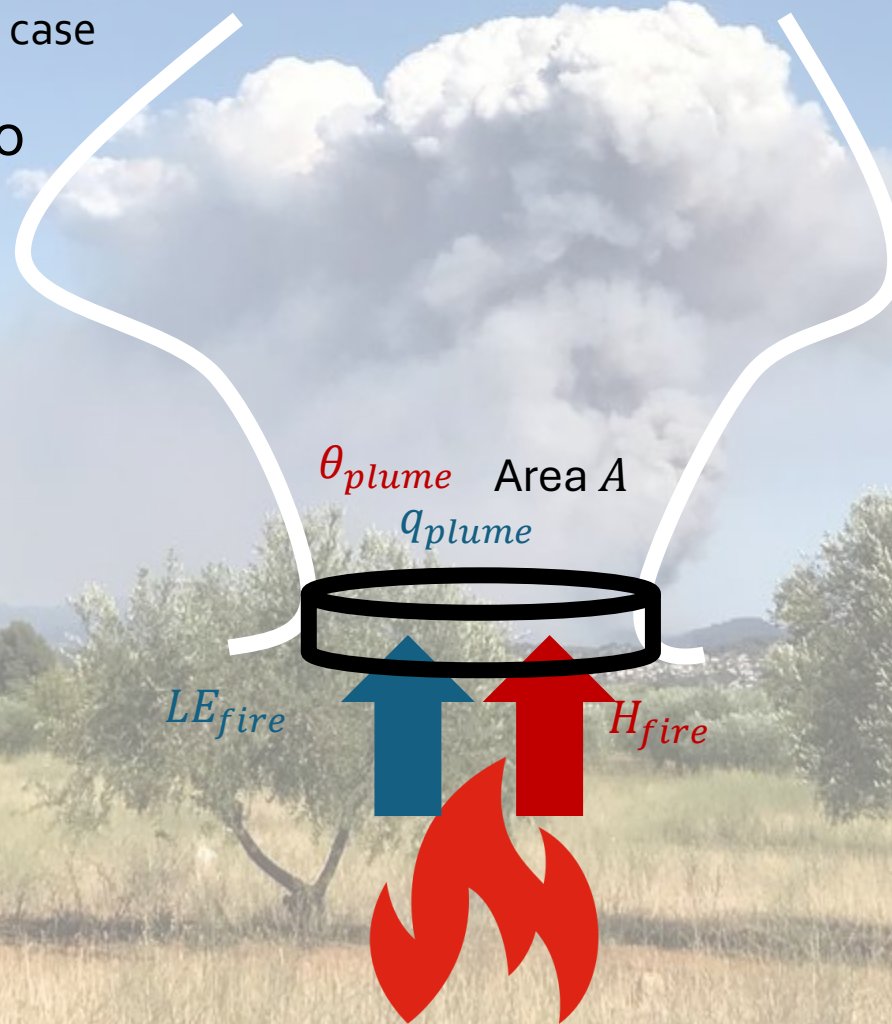
Open the “class-Martorell simplified” case

Exercise 1: What happens to

- A_{plume}
- θ_{plume}
- q_{plume}

When you *increase* the following fire properties:

- l_{fire}
- ω_{fire}
- C_{fire}
- v_{fire}
- $C_{q,fire}$
- rl_{fire}



Discuss in your groups and make a causal diagram (e.g. $l_{fire} \uparrow \rightarrow A_{plume} \uparrow$)

Exercise 1 - Discussion

A_{plume} can rise because l_{fire} increases or d_{fire} increases

θ_{plume} can rise because:

- ω_{fire} increases (more fuel $\rightarrow$ more energy released by burning 1 m² $\rightarrow$ higher θ_{plume})
- C_{fire} increases (more energy-dense fuel $\rightarrow$ more energy released by burning 1 m² $\rightarrow$ higher θ_{plume})
- v_{fire} increases (fuel burns more quickly $\rightarrow$ more energy released each second $\rightarrow$ higher θ_{plume})
- rl_{fire} decreases (less fuel energy is “lost” to radiation $\rightarrow$ higher θ_{plume})

q_{plume} : Same reaction to ω_{fire} , v_{fire} , does not respond to rl_{fire} , C_{fire} (but to $C_{q,fire}$)

$$\theta_{plume} = C_{fire} \times \omega_{fire} \times \frac{v_{fire}}{d_{fire}} \times (1 - rl_{fire}) / (\rho \times c_p \times w_{plume})$$

Exercise 1

$$A_{plume} = A_{fire} = L_{fire} \times d_{fire}$$

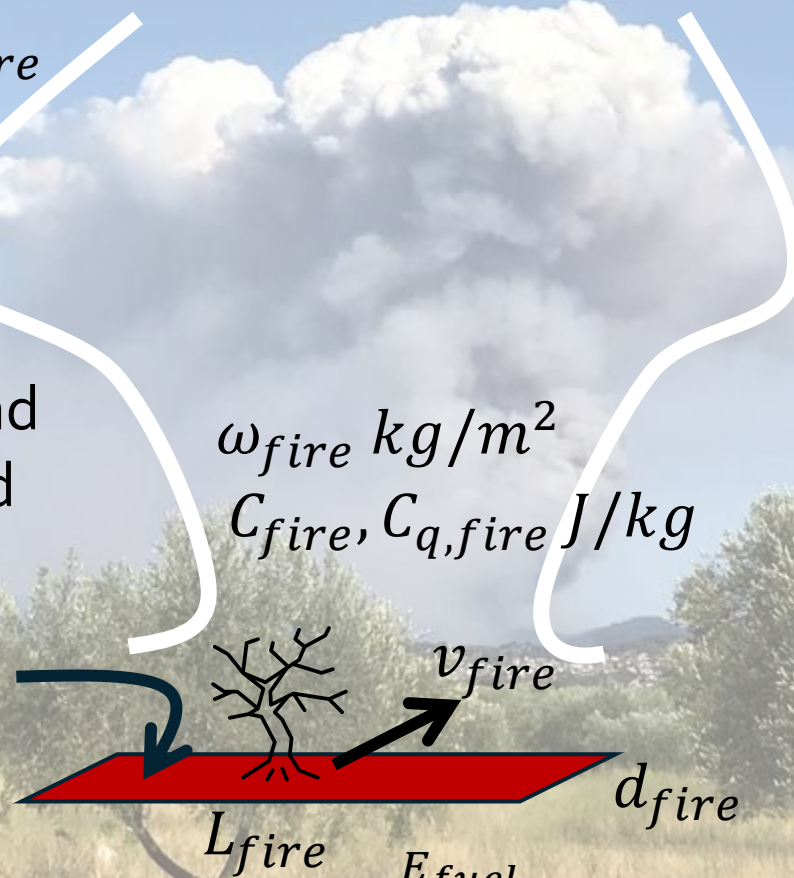
$$E_{fuel} = C_{fire} \times \omega_{fire} [J]$$

$$q_{fuel}$$

$$= C_{q,fire} \times \omega_{fire} [kg]$$

How quickly are fuel energy and water converted into increased air temperature and humidity?

Time it takes to burn the A_{fire} red square $t = d_{fire}/v_{fire}$



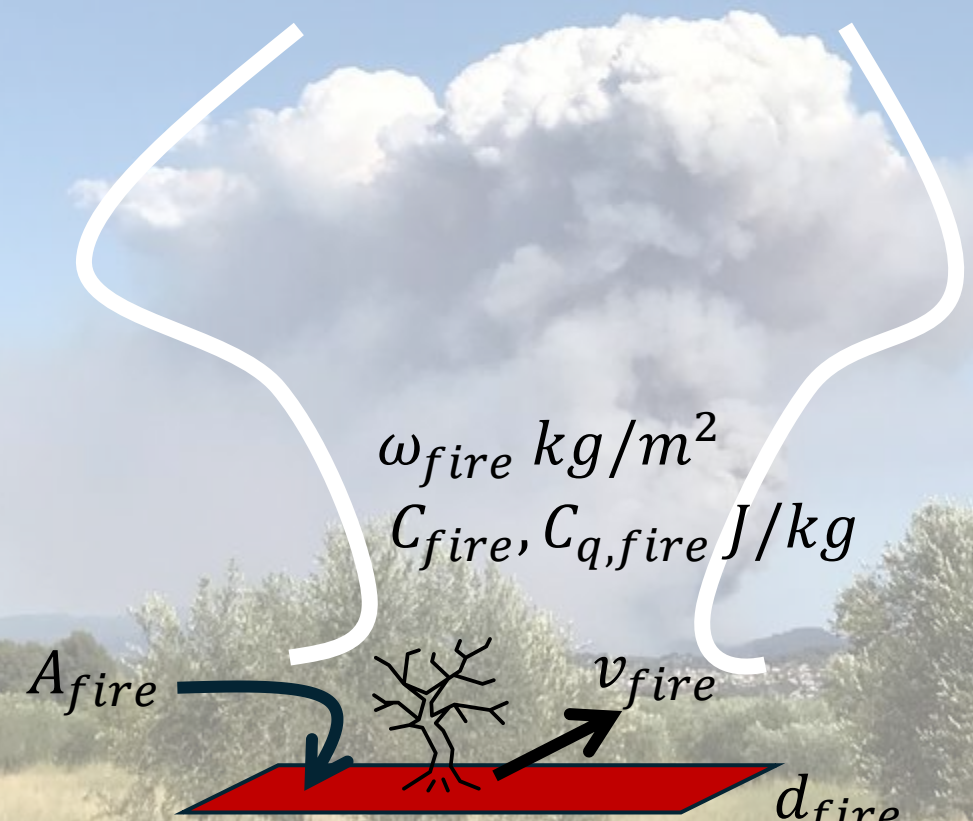
So energy flux is:

$$\frac{E_{fuel}}{t} = C_{fire} \times \omega_{fire} \times \frac{v_{fire}}{d_{fire}} \quad (\text{similar for } q_{fuel})$$

Of this energy, a fraction rl_{fire} is "lost" to radiation, so the total amount of energy

entering the plume is $H_{fire} = C_{fire} \times \omega_{fire} \times \frac{v_{fire}}{d_{fire}} \times (1 - rl_{fire})$

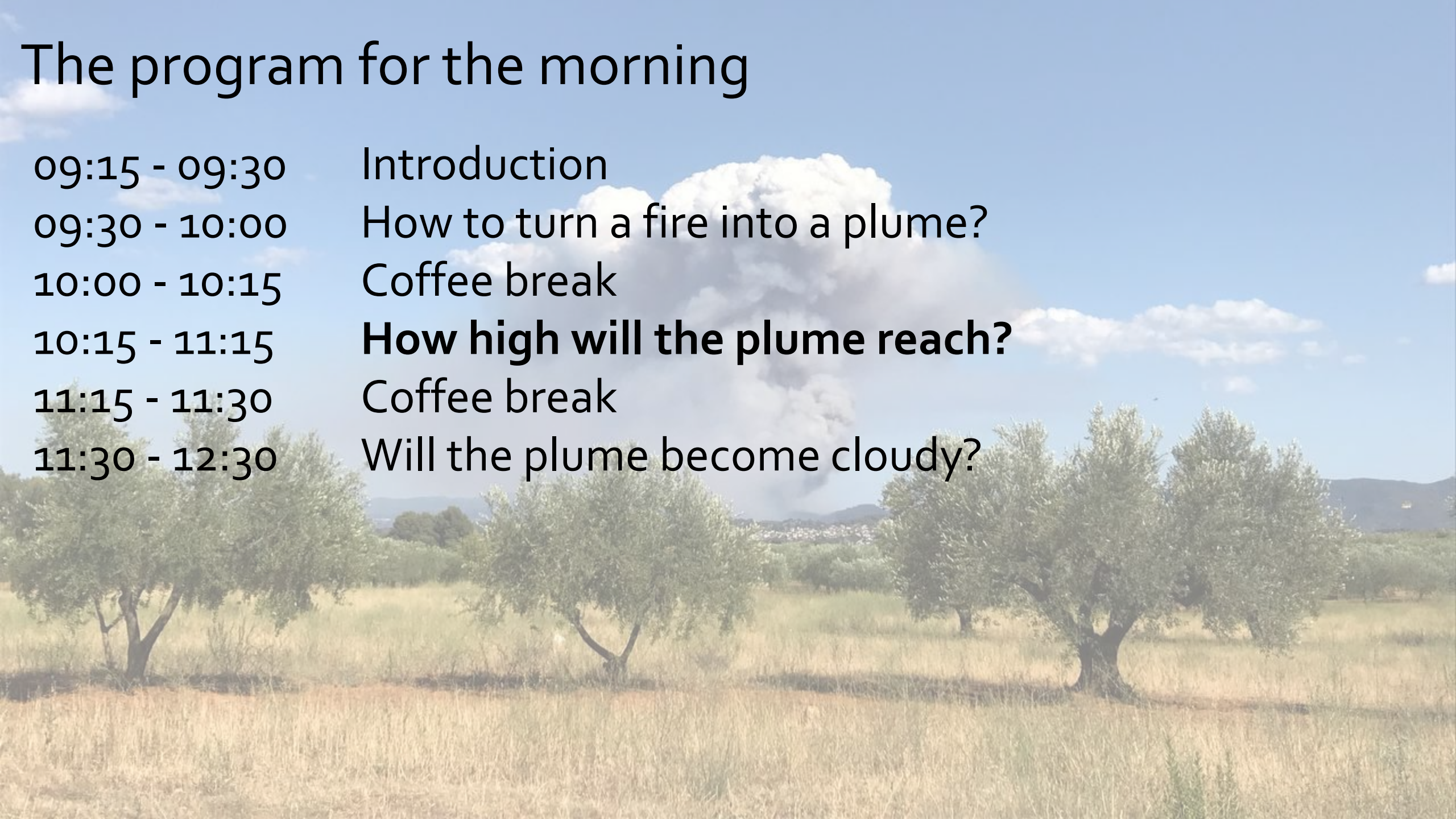
Break



The diagram illustrates a fire plume rising from a fuel source. A red parallelogram represents the fuel bed, with a tree icon on top. A blue arrow labeled A_{fire} points down to the fuel bed. A black arrow labeled v_{fire} points up from the fuel bed. A white outline represents the fire plume, which is a large, billowing cloud-like shape. Inside the plume, the text $\omega_{fire} \text{ kg/m}^2$ and $C_{fire}, C_{q,fire} \text{ J/kg}$ is written. Below the fuel bed, the text L_{fire} and d_{fire} is written.

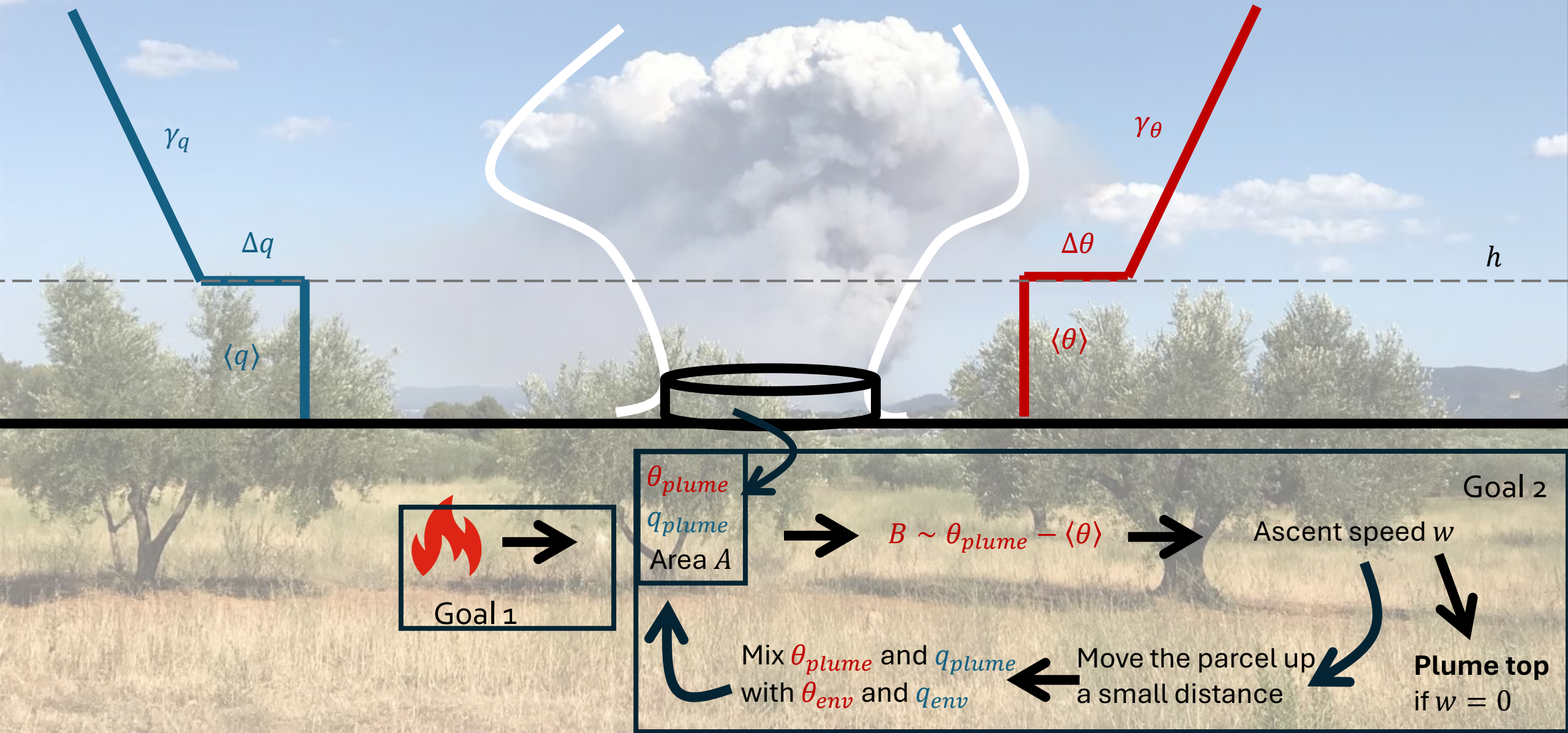
$$H_{fire} = C_{fire} \times \omega_{fire} \times (1 - r_{l_{fire}}) \times \frac{v_{fire}}{d_{fire}}$$
$$E_{fire} = C_{q,fire} \times \omega_{fire} \times \frac{v_{fire}}{d_{fire}}$$

The program for the morning



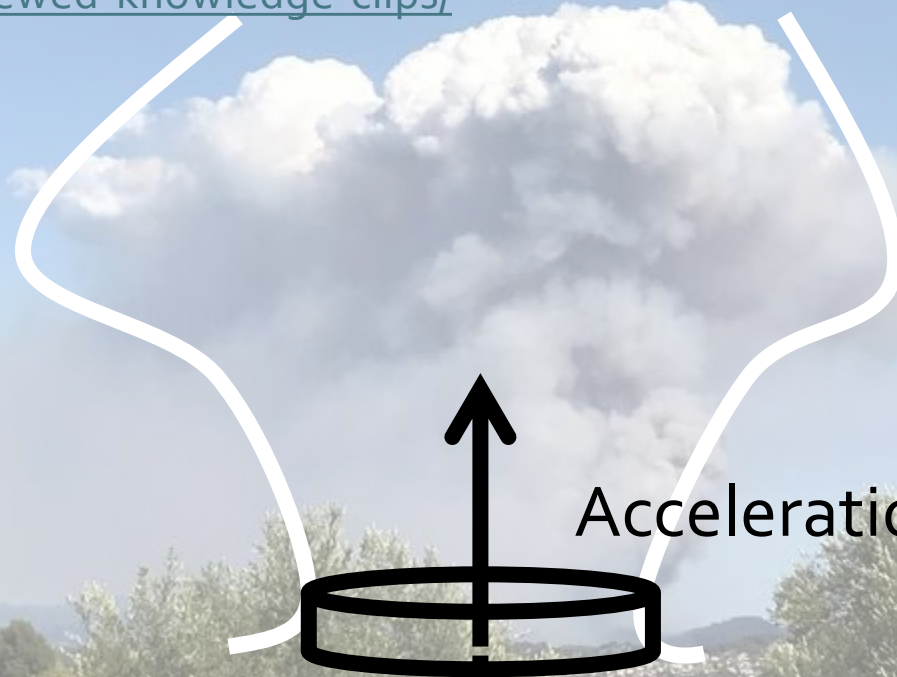
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An idealised plume: Determining the plume top



From buoyancy to ascent

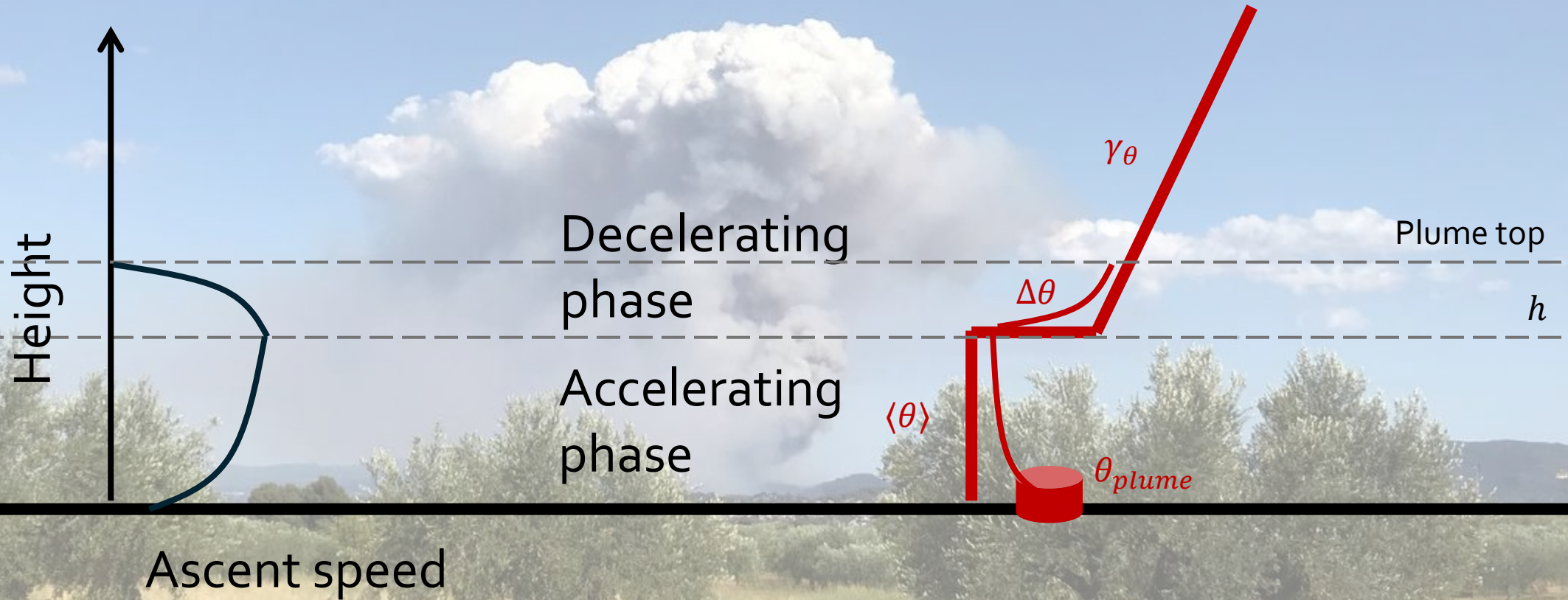
See also knowledge clip **1. Why do plumes rise?** on
<https://wildfiredataportal.eu/science/ewed-knowledge-clips/>



Acceleration: Buoyancy $\sim \theta_{plume} - \langle \theta \rangle$

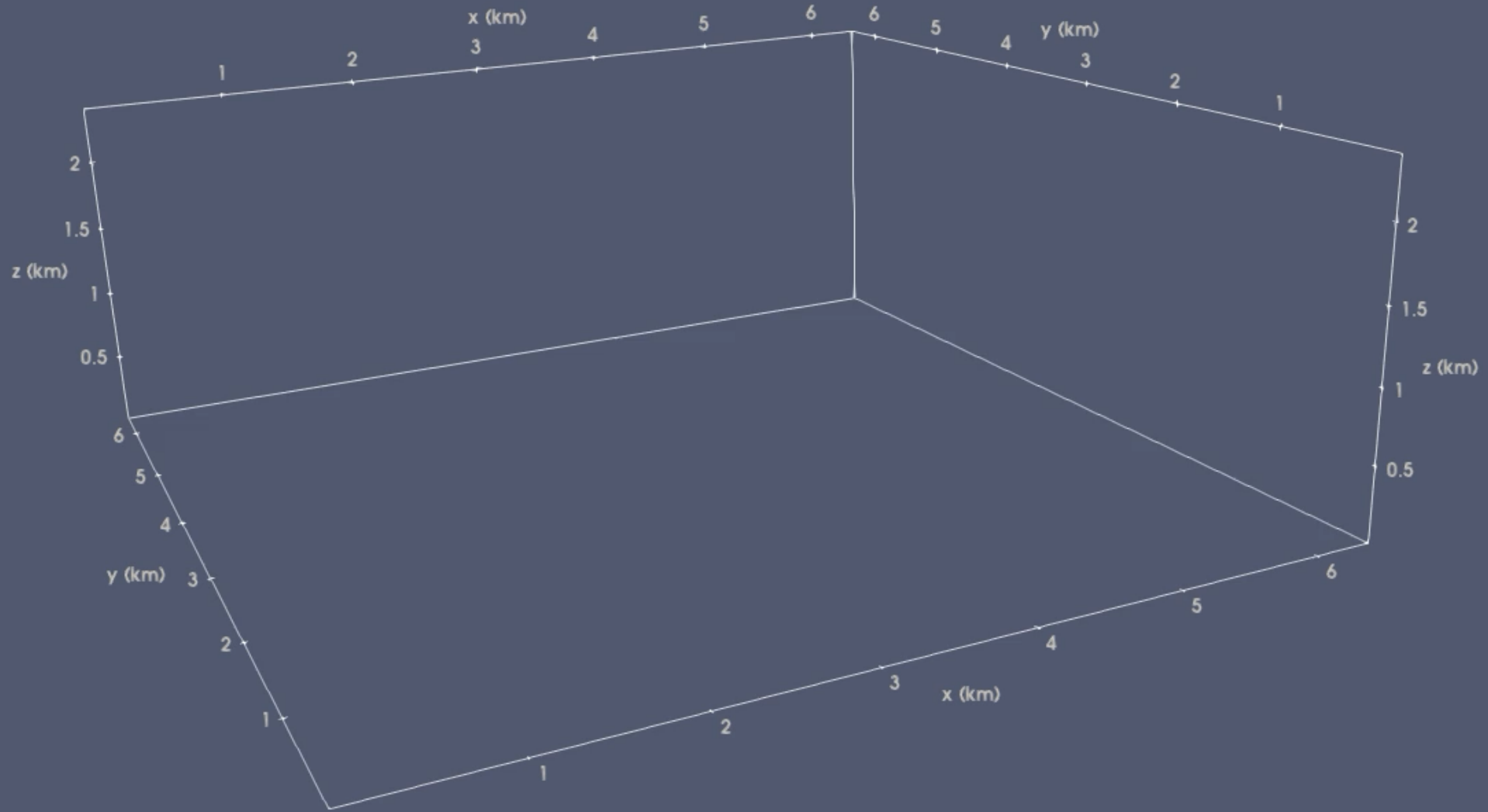
Deceleration:
Negative buoyancy $\sim \theta_{plume} - \langle \theta \rangle < 0$
"Drag"

From buoyancy to ascent



Plume top in our model is the highest point the plume will reach

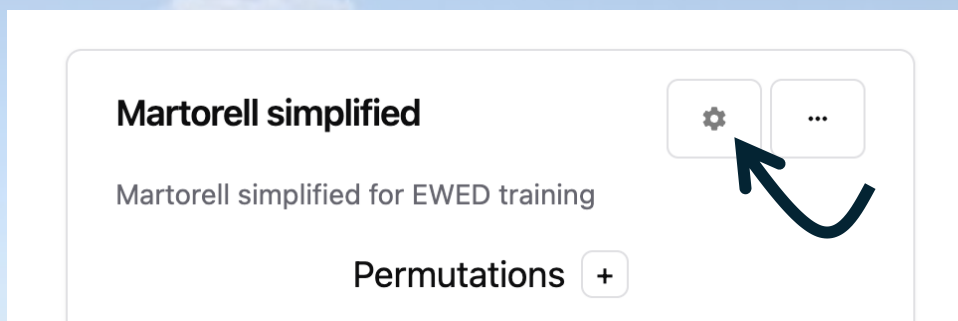
From buoyancy to ascent



Exercise 2 – What determines the plume top?

<https://wildfiredataportal.eu/science/modeling/>

Open the “class-Martorell simplified” case



Plot vertical profiles of

- Potential temperature
- Vertical velocity

Exercise 2.1: Identify for the plume:

- Where buoyancy is positive and negative
- Where the plume top is

Fire

Fire switch



L_{fire}

100

m

d_{fire}

10

m

$h_{0, \text{fire}}$

20

m

C_{fire}

18620800

J kg⁻¹

$C_{q, \text{fire}}$

0

kg kg⁻¹

ω_{fire}

0.1

kg m⁻²

V_{fire}

1.5

m s⁻¹

rl_{fire}

0.7

-

Navigate to 17:00

Run

Exercise 2 – What determines the plume top?

Exercise 2.2 – Discuss:

How do the plume buoyancy and plume top evolve through the day? How do the changing h and $\Delta\theta$ affect the plume top?

Exercise 2.3 – Sensitivity analyses (cases on <https://wildfiredataportal.eu/science/modeling/>)

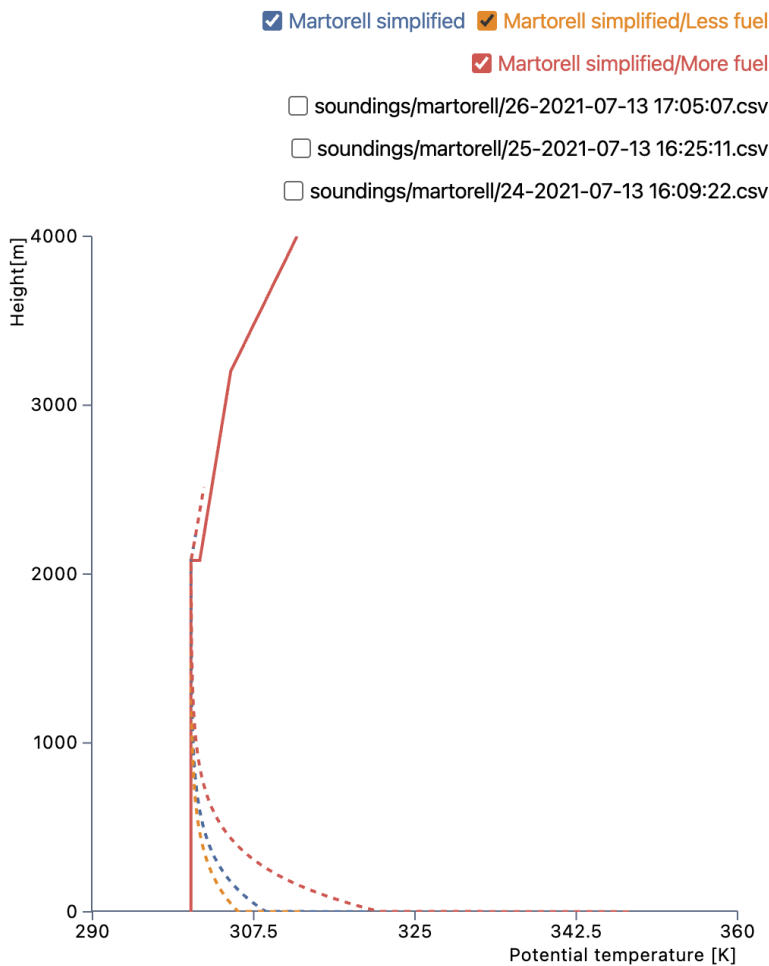
Test the sensitivity to **two** of the following variables (pick 1-2 or 3-4):

1. ω_{fire} to 1 and 2 kg/kg ("class-Martorell simplified_Fire_Fuel")
2. $w'\theta'$ to 0.25 and 0.35 Km/s ("class-Martorell simplified_Fire_surface")
3. l_{fire} to 2000 and 10,000 m ("class-Martorell simplified_Fire_Area")
4. γ_{θ} to 0.005, 0.009 and 0.001, 0.009 K/m ("class-Martorell simplified_Fire_Lapse")

Explain, using causal diagrams, the changes in **buoyancy, vertical velocity and plume top height** as you increase your control variable, at 17:00 UTC

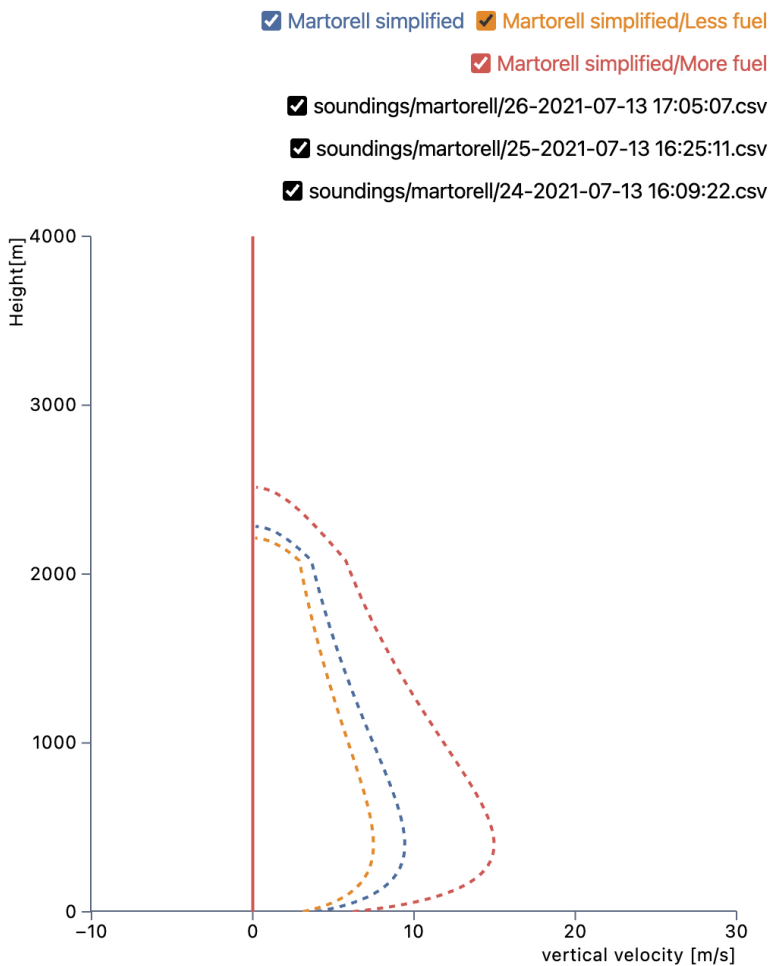
Exercise 2 – Discussion: Fuel density

Vertical profiles



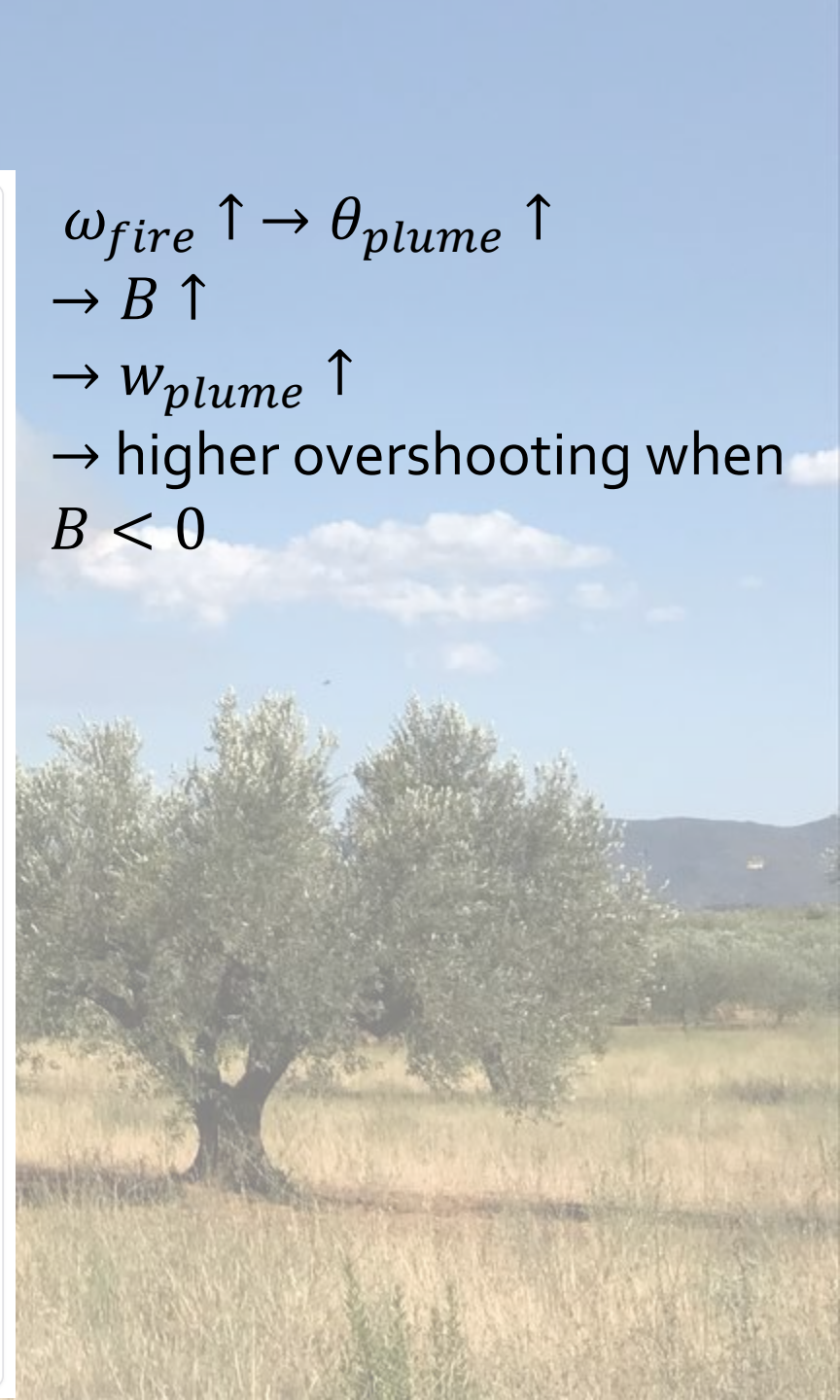
Time (UTC): 17:00

Vertical profiles



Time (UTC): 17:00

$\omega_{fire} \uparrow \rightarrow \theta_{plume} \uparrow$
 $\rightarrow B \uparrow$
 $\rightarrow w_{plume} \uparrow$
 $\rightarrow$ higher overshooting when $B < 0$



Exercise 2 – Discussion: Environmental surface heat flux

$$w'\theta' \uparrow \rightarrow 1. \langle \theta \rangle \uparrow \text{ and } 2. h \uparrow$$

Vertical profiles

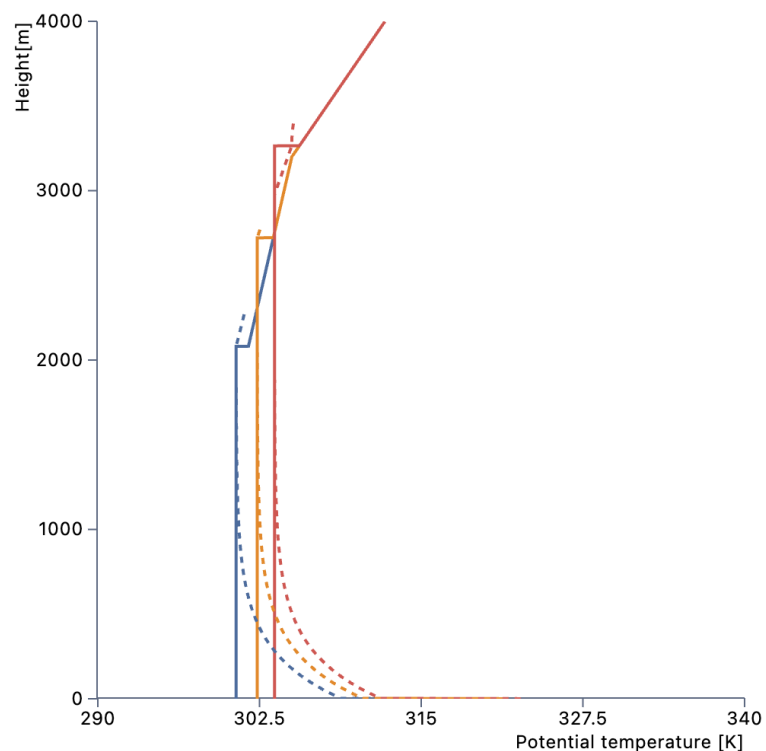
☒ Martorell simplified ☒ Martorell simplified/High H (0.25)

☒ Martorell simplified/Very high H (0.35)

☐ soundings/martorell/26-2021-07-13 17:05:07.csv

☐ soundings/martorell/25-2021-07-13 16:25:11.csv

☐ soundings/martorell/24-2021-07-13 16:09:22.csv



variable: Potential temperature [K] ▾

Time (UTC): 17:00

Vertical profiles

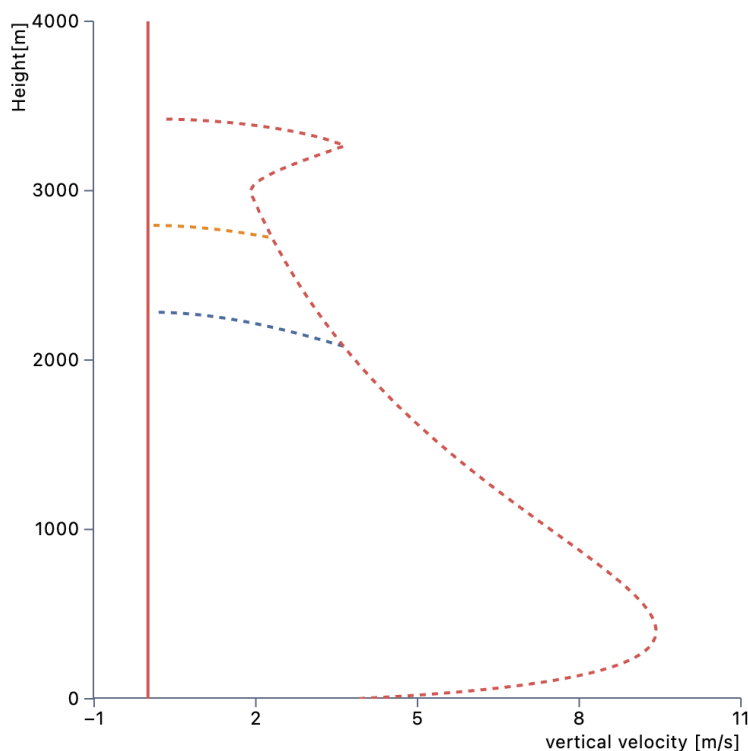
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☒ soundings/martorell/24-2021-07-13 16:09:22.csv



variable: vertical velocity [m/s] ▾

Time (UTC): 17:00

1.
 $\langle \theta \rangle \uparrow \rightarrow \theta_{plume} \uparrow$,
But $B = \theta_{plume} - \langle \theta \rangle$ stays
the same, so
 w_{plume} stays the same inside
the mixed layer

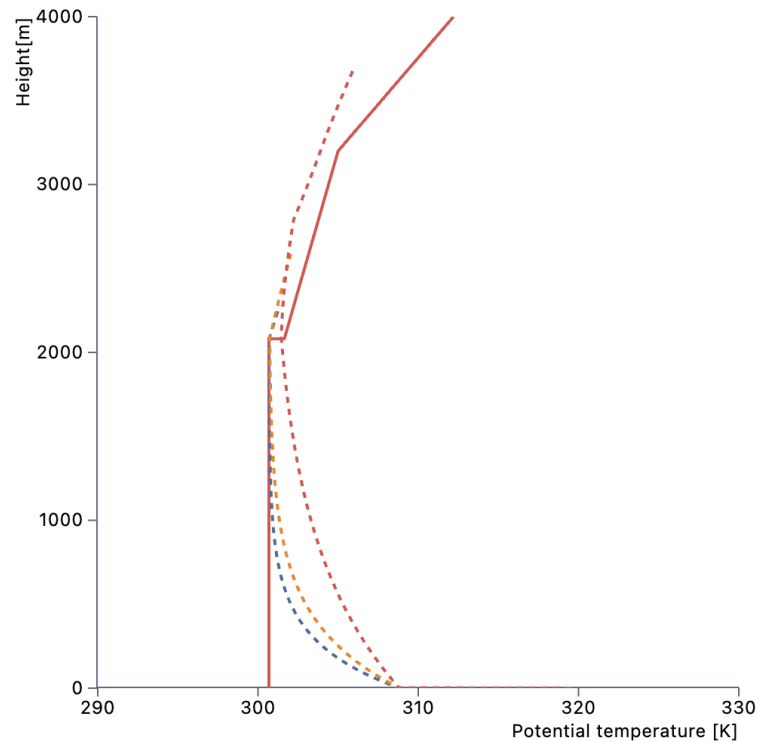
2.
 $h \uparrow \rightarrow B < 0$ happens higher
Deceleration happens higher
Plume top rises
*Unexpected jump at the
highest surface flux!*

Exercise 2 – Discussion: Fire size

Vertical profiles

- ☒ Martorell simplified ☒ Martorell simplified/Larger fire
☒ Martorell simplified/Massive fire

- ☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv



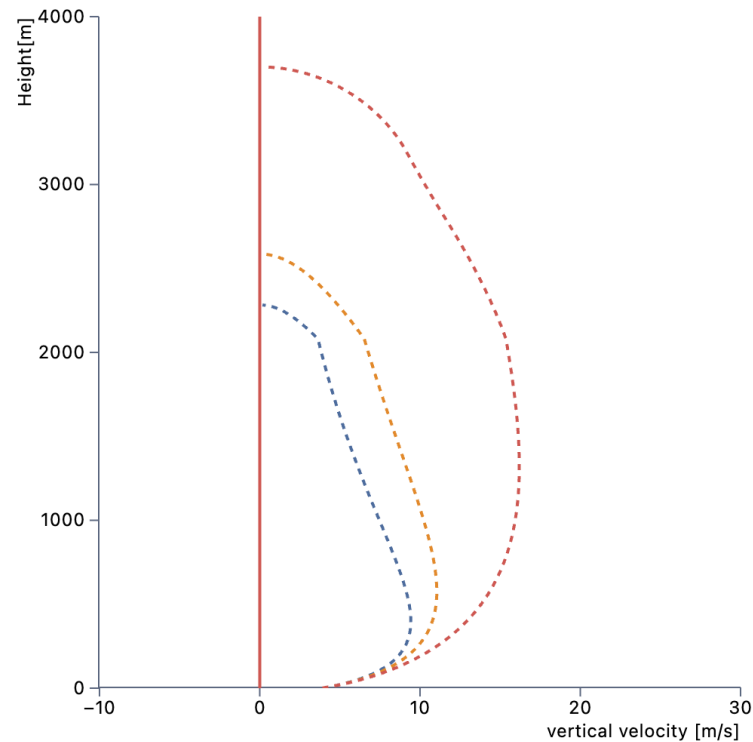
variable: Potential temperature [K] ▾

Time (UTC): 17:00

Vertical profiles

- ☒ Martorell simplified ☒ Martorell simplified/Larger fire
☒ Martorell simplified/Massive fire

- ☒ soundings/martorell/26-2021-07-13 17:05:07.csv
☒ soundings/martorell/25-2021-07-13 16:25:11.csv
☒ soundings/martorell/24-2021-07-13 16:09:22.csv

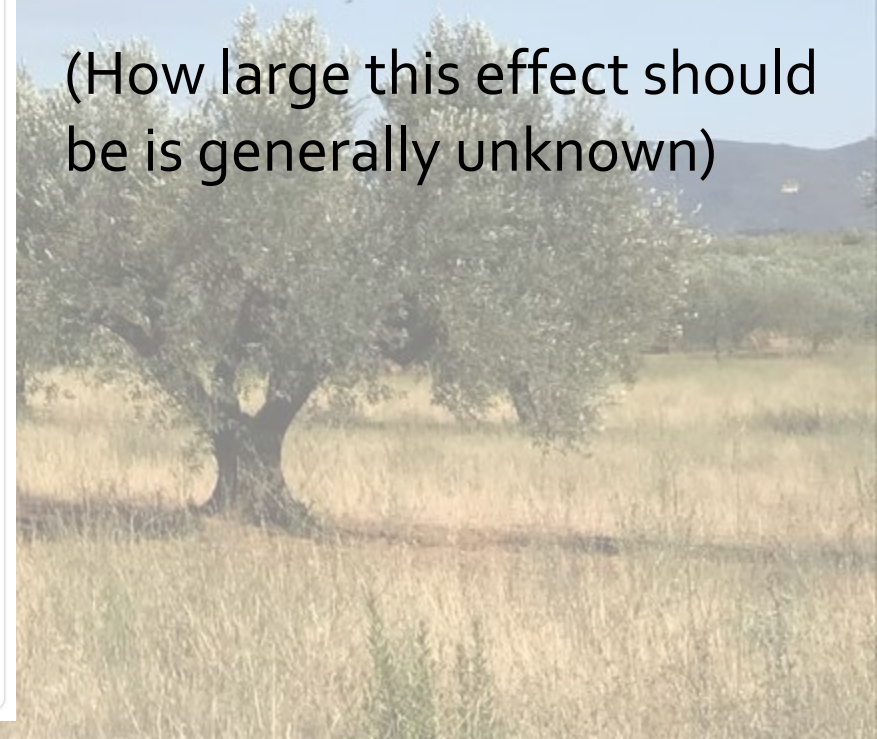


variable: vertical velocity [m/s] ▾

Time (UTC): 17:00

$l_{fire} \uparrow \rightarrow A_{plume} \uparrow$
→ entrainment efficiency ↓
→ less mixing
→ higher B below h
→ Higher w_{plume}
→ higher overshooting

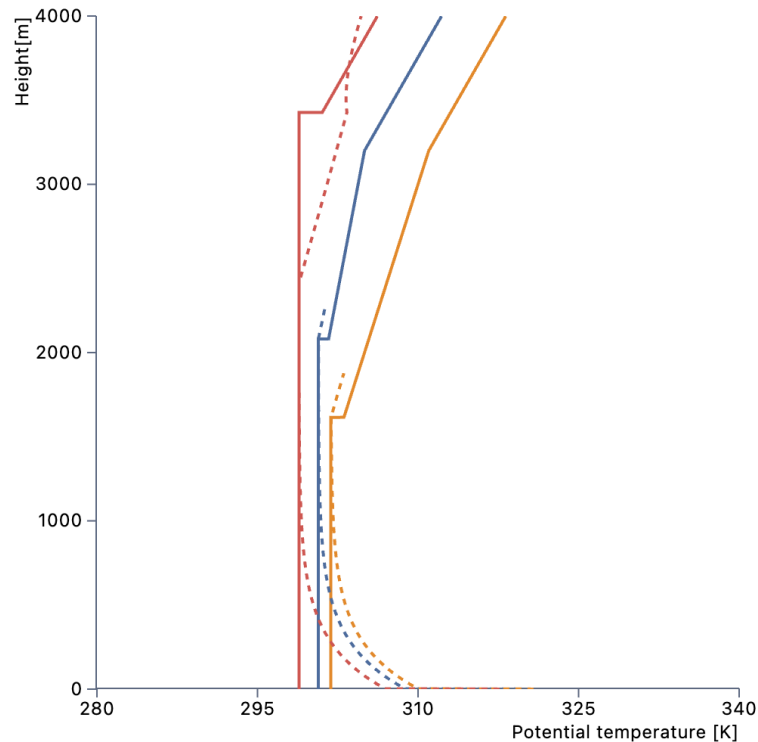
(How large this effect should be is generally unknown)



Exercise 2 – Discussion: Lapse rate

Vertical profiles

- ☒ Martorell simplified
 ☒ Martorell simplified/Stable free troposphere (0.005)
 ☒ Martorell simplified/Unstable free troposphere (0.001)
- ☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv

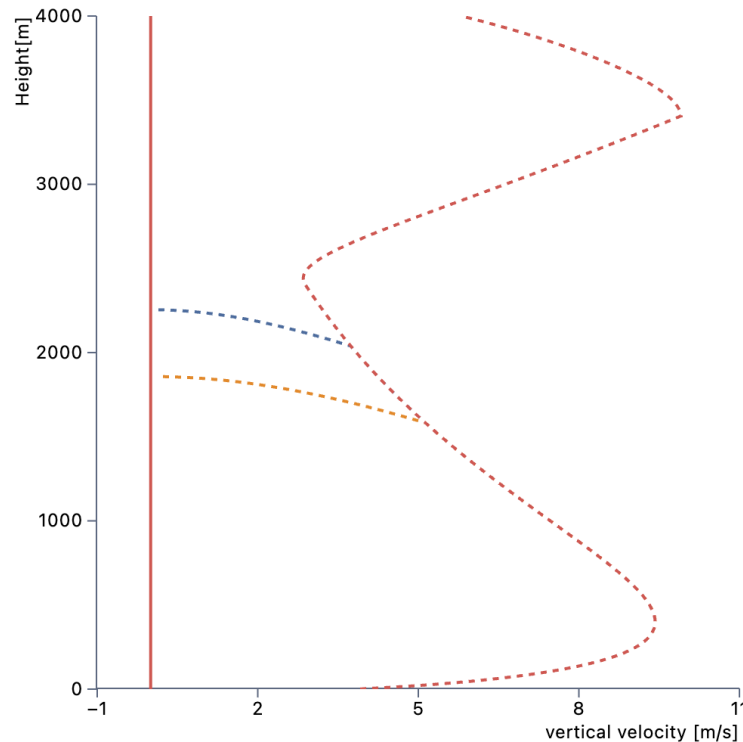


variable: Potential temperature [K] ▾

Time (UTC): 17:00

Vertical profiles

- ☒ Martorell simplified
 ☒ Martorell simplified/Stable free troposphere (0.005)
 ☒ Martorell simplified/Unstable free troposphere (0.001)
- ☒ soundings/martorell/26-2021-07-13 17:05:07.csv
☒ soundings/martorell/25-2021-07-13 16:25:11.csv
☒ soundings/martorell/24-2021-07-13 16:09:22.csv



variable: vertical velocity [m/s] ▾

Time (UTC): 16:40

$\gamma_\theta \downarrow \rightarrow 1. \langle \theta \rangle \downarrow$ and $2. h \uparrow$

1.

$\langle \theta \rangle \downarrow \rightarrow \theta_{plume} \downarrow$,

But $B = \theta_{plume} - \langle \theta \rangle$ stays the same, so

w_{plume} first stays the same

2.

For $\gamma_\theta \uparrow$:

$h \downarrow \rightarrow B < 0$ happens lower

Deceleration happens lower

Plume top reduces

For $\gamma_\theta \downarrow$:

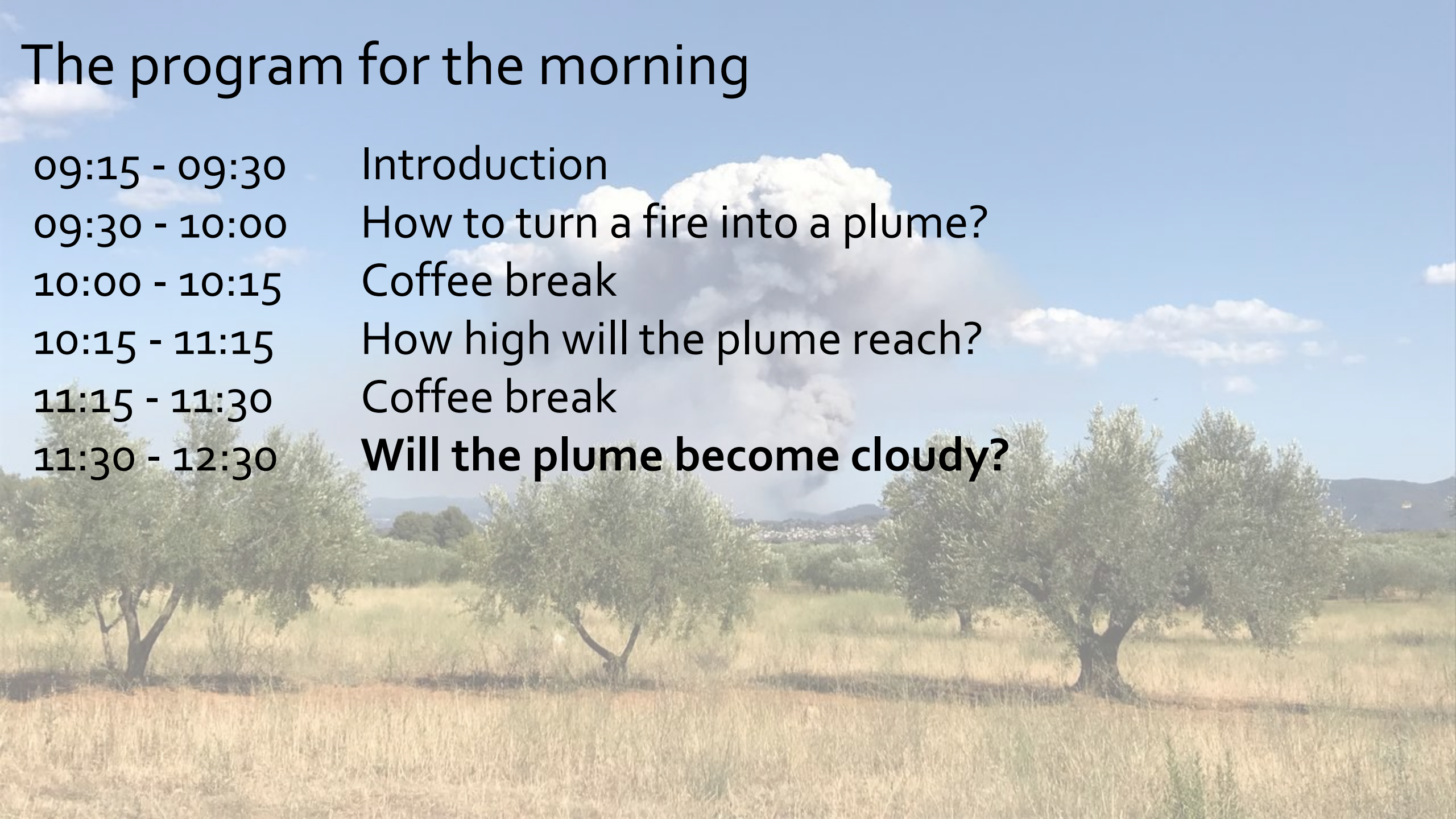
$h \uparrow \rightarrow B > 0$ inside BL

Big rise in w and plume top

Break



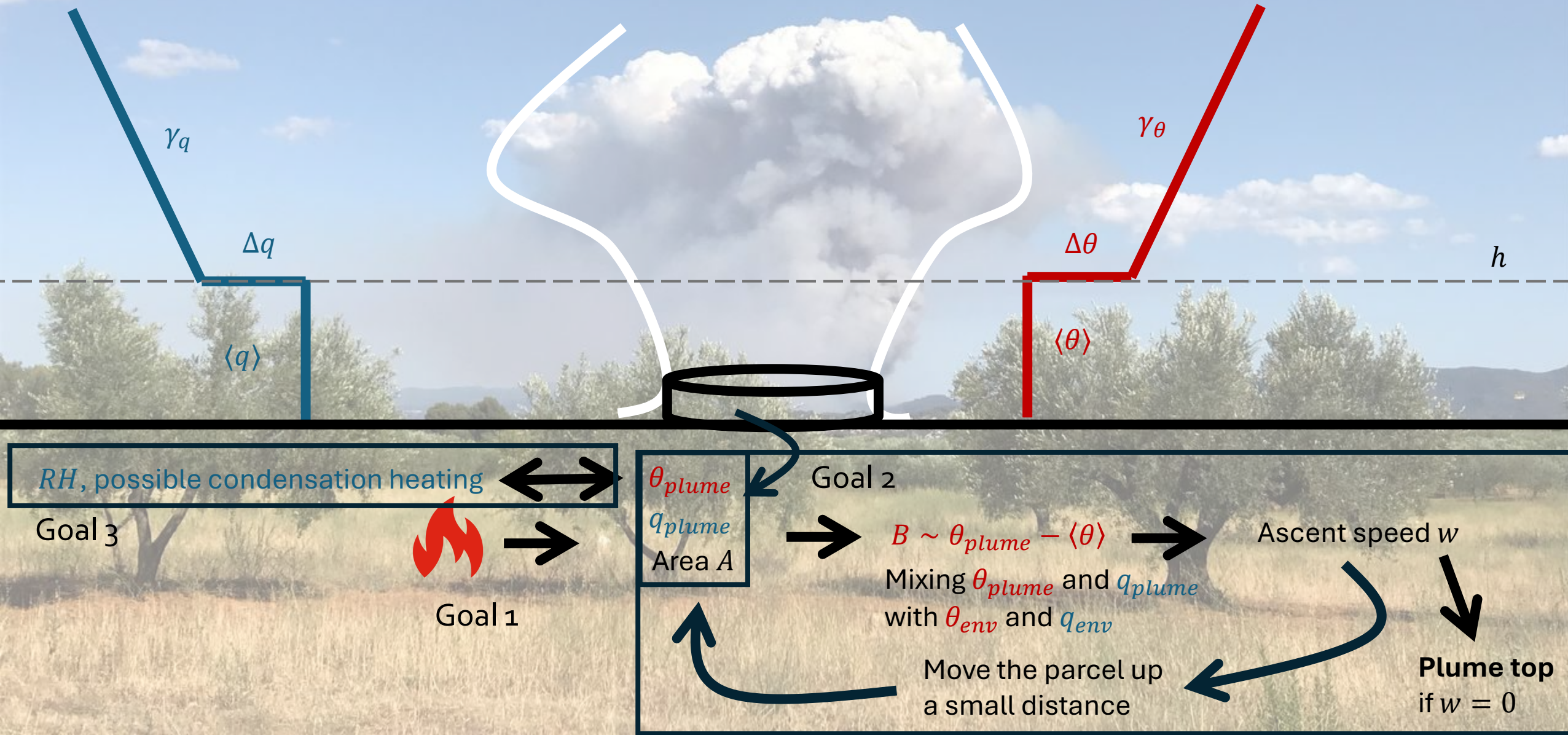
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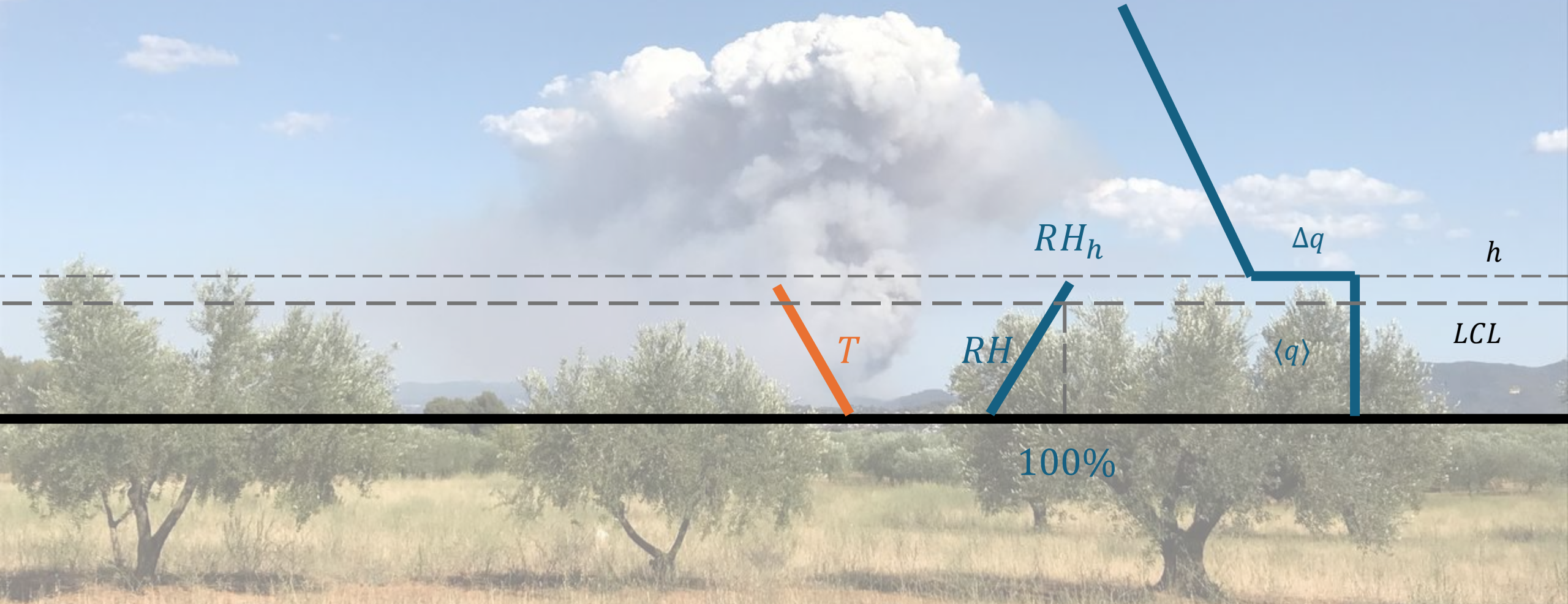
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Will the plume become cloudy?

See also <https://wildfiredatportal.eu/science/ewed-knowledge-clips/>, Clip 2. Lifting condensation level

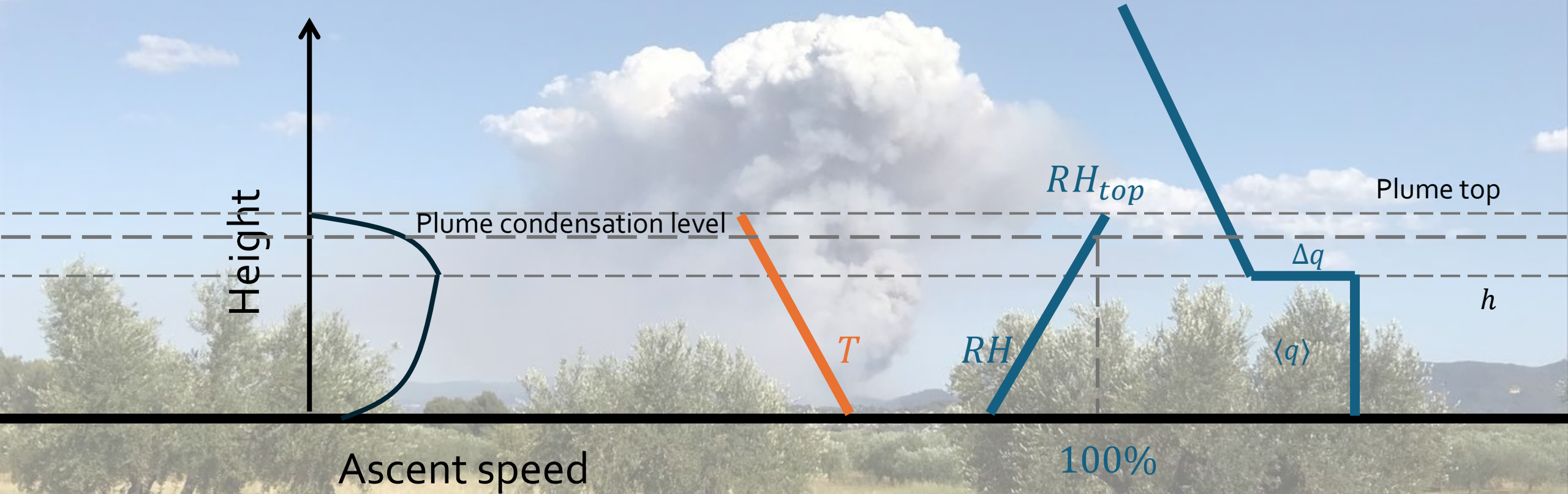


Will the ~~plume~~ boundary layer become cloudy?



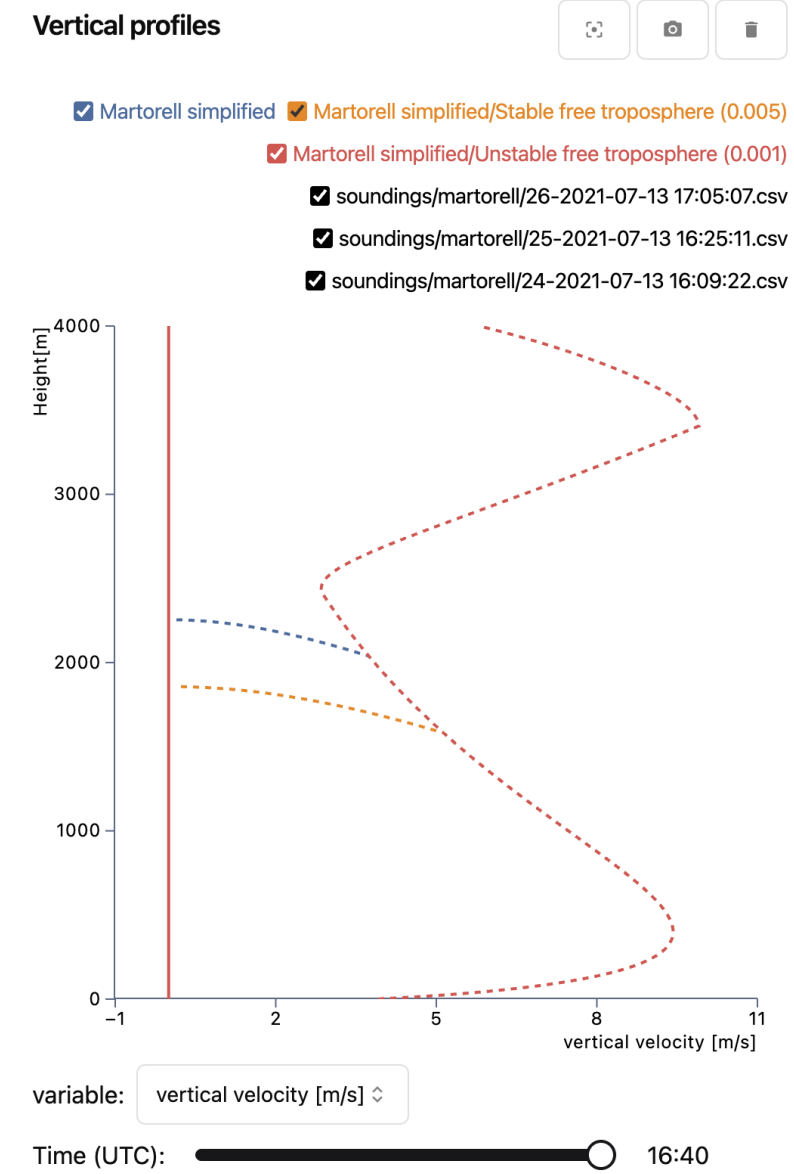
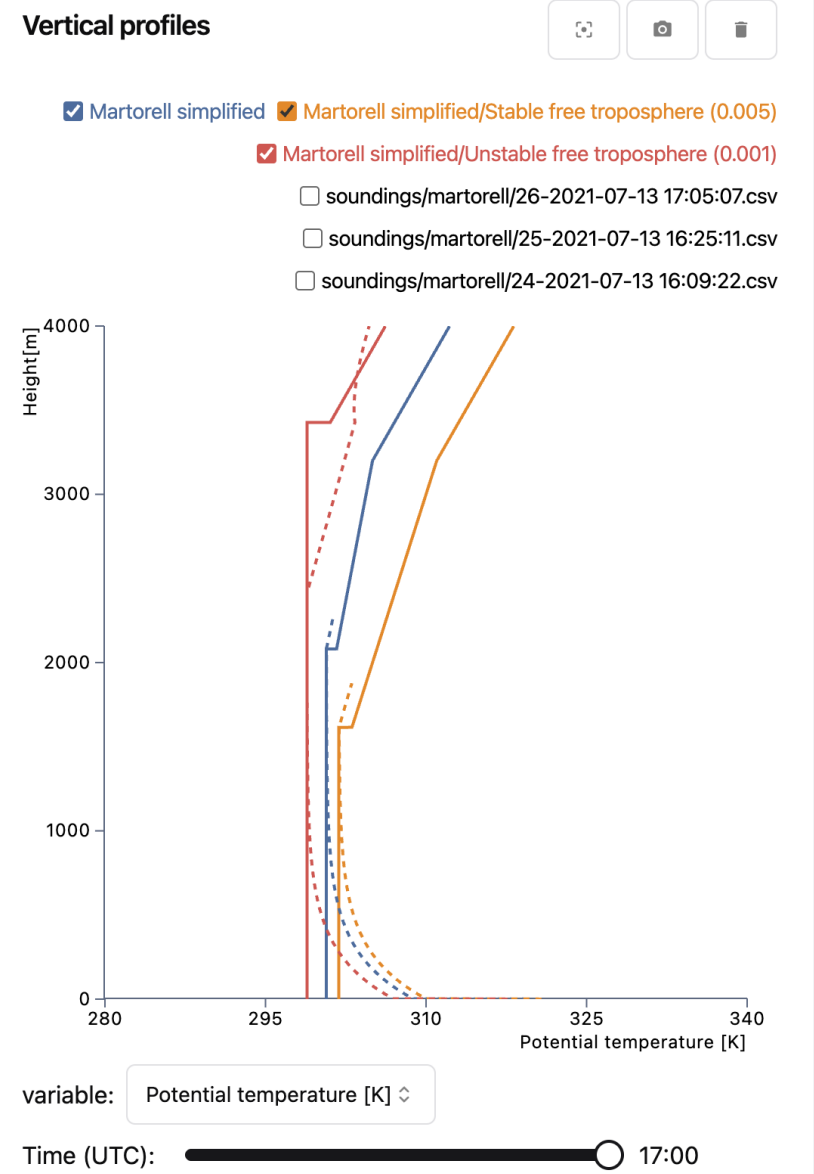
$\Rightarrow$ If RH_h approaches 100%, we have clouds near h

Will the plume become cloudy?



$\Rightarrow$ If RH_{top} approaches 100%, the plume is cloudy

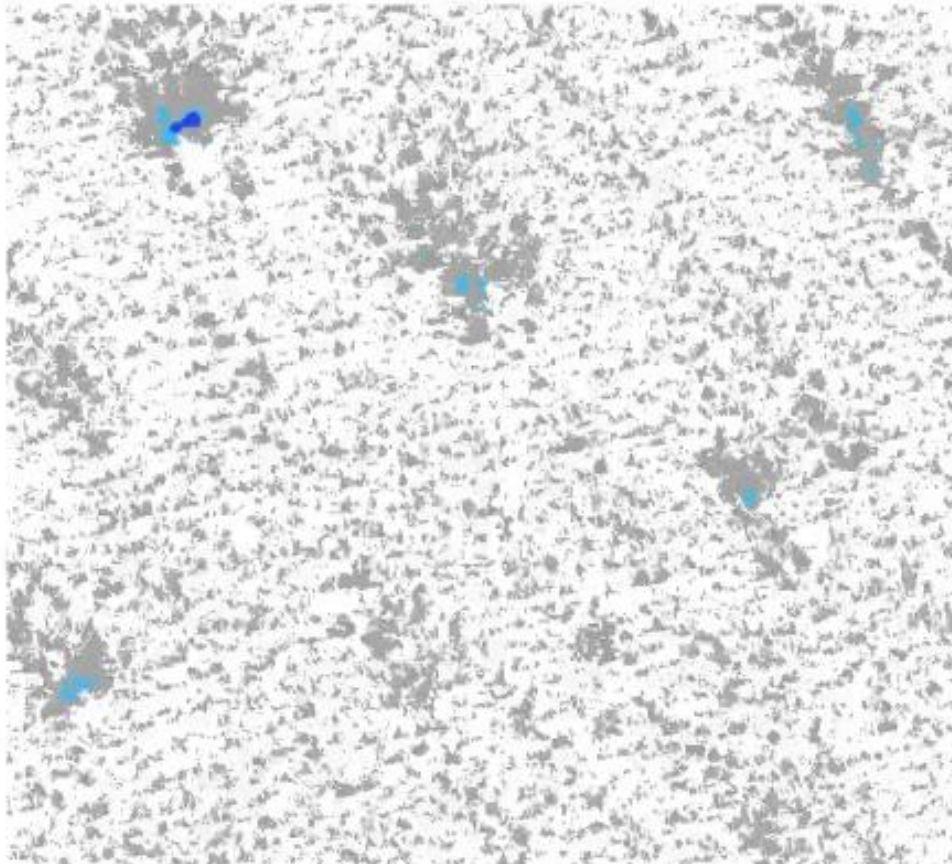
What happens when we get condensation?



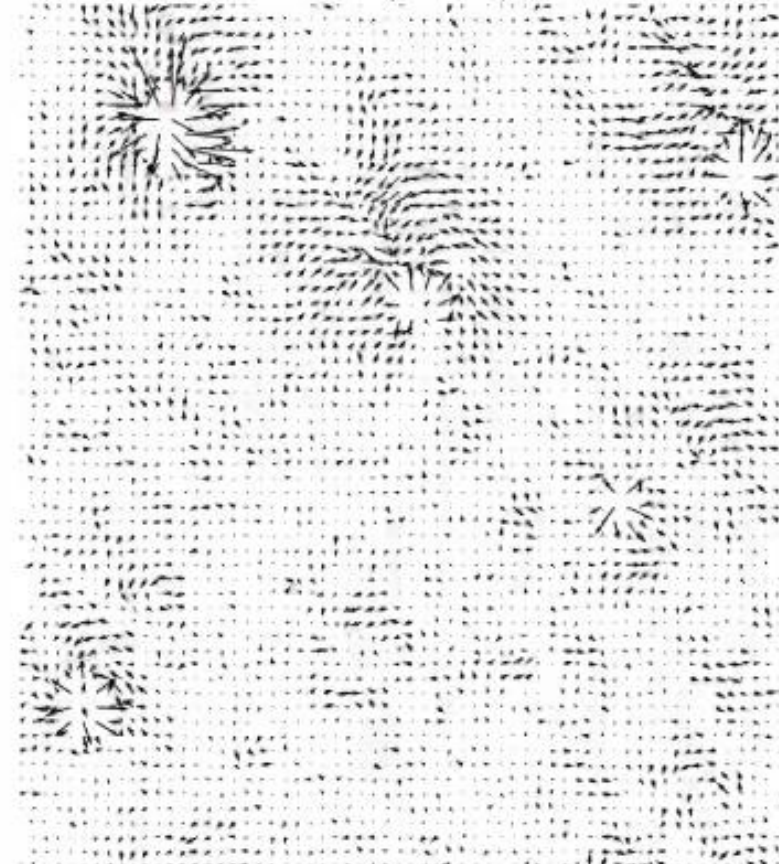
Why does it matter that we get condensation?

Cold pool identifications in shallow cumulus
DALES run: 3072×3072 grids cell, 50 m resolutions

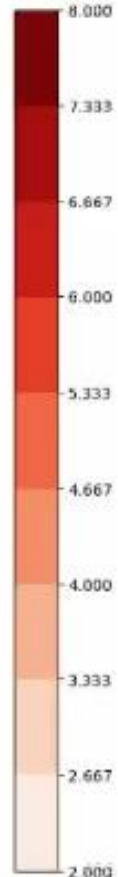
Clouds, Rain, Cold Pools



Horizontal Velocity Anomaly @surface



Magnitude of Horizontal Velocity [m/s]



Clouds Rain Cold pools (-1 K) Cold pools (-2 K)

Exercise 3 – What determines RH at plume top?

Exercise 3.1: Explain, for the standard case, the vertical structure of the plume's relative humidity, using vertical profiles of RH , q , θ and T , at 10.00, 17.00 UTC

Exercise 3.2 – Sensitivity experiments. Take your same experiments:

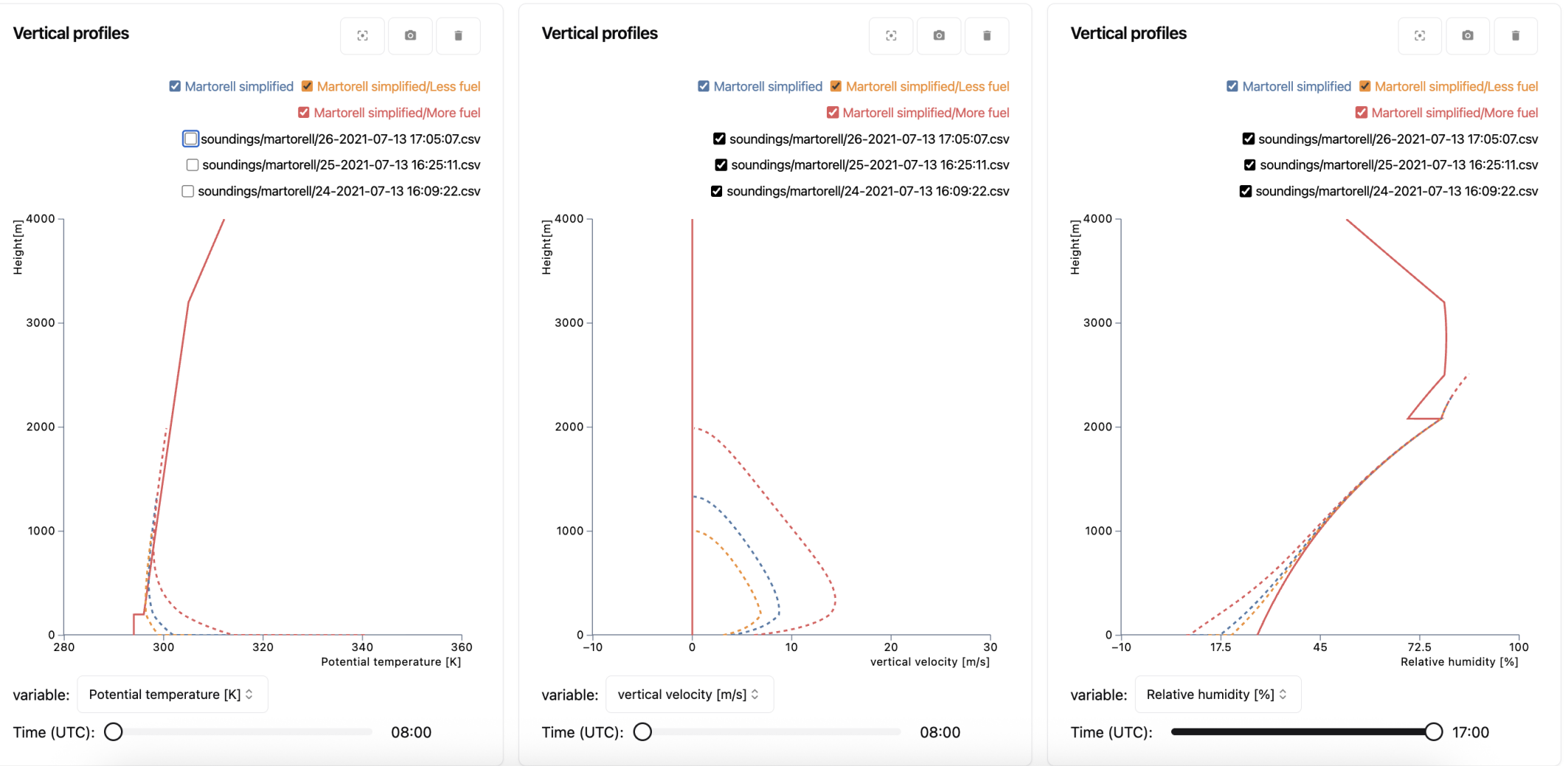
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3. l_{fire} to 2000 and 10,000
4. γ_{θ} to 0.005, 0.009 and 0.001, 0.009 K/m

Plot vertical profiles of potential temperature, vertical velocity **and relative humidity**. Explain, using causal diagrams, plume RH sensitivity to your control variables, at 17:00 UTC.

Exercise 3.3 (Bonus): Investigate the sensitivity to adding moisture to the background atmosphere (class-Martorell simplified_Fire_Moisture)

Exercise 3.2 – Discussion: Fuel density

First $\omega_{fire} \uparrow \rightarrow \theta_{plume} \uparrow \rightarrow RH_{plume} \downarrow$ until all are mixed towards the environmental θ, q
Then $\omega_{fire} \uparrow \rightarrow h \uparrow \rightarrow RH_{plume\ top} \uparrow$



Exercise 3.2 – Discussion: Environmental surface heat flux

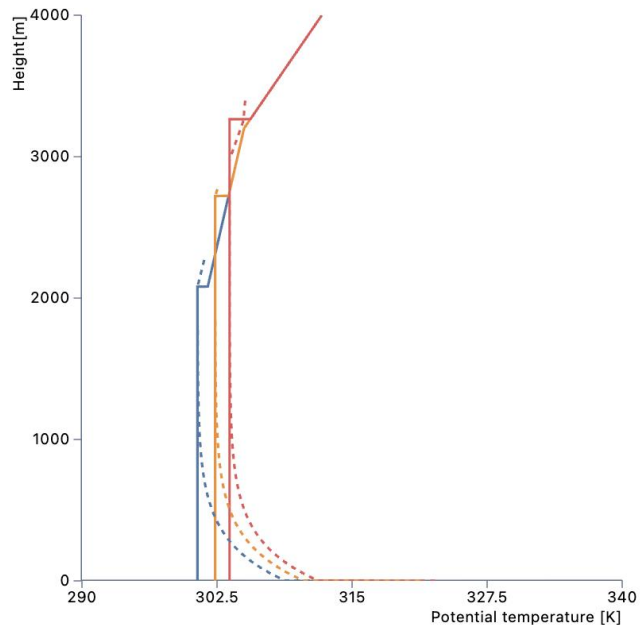
$w'\theta' \uparrow \rightarrow 1. \langle \theta \rangle \uparrow$ and $2. h \uparrow$

1. $\langle \theta \rangle \uparrow \rightarrow RH \downarrow$ in both plume and env

2. $h \uparrow \rightarrow RH_{plume\ top} \uparrow$ and condensation.

Vertical profiles

- ☒ Martorell simplified ☒ Martorell simplified/High H (0.25)
☒ Martorell simplified/Very high H (0.35)
- ☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv

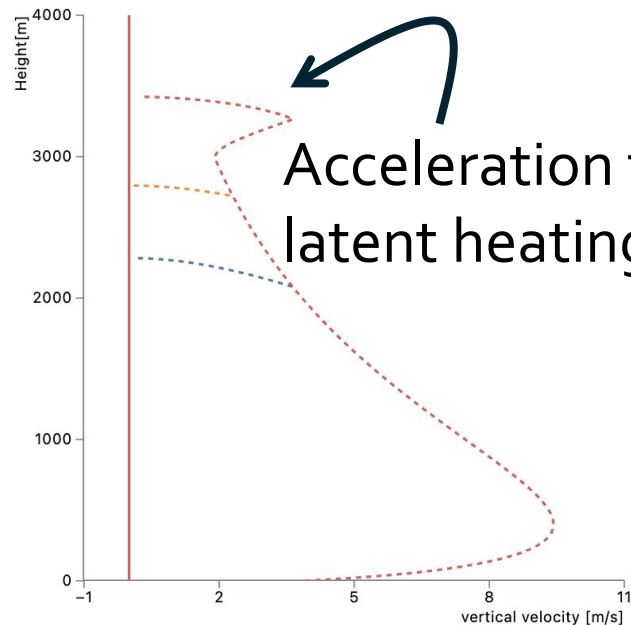


variable: Potential temperature [K] ▾

Time (UTC): 17:00

Vertical profiles

- ☒ Martorell simplified ☒ Martorell simplified/High H (0.25)
☒ Martorell simplified/Very high H (0.35)
- ☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv

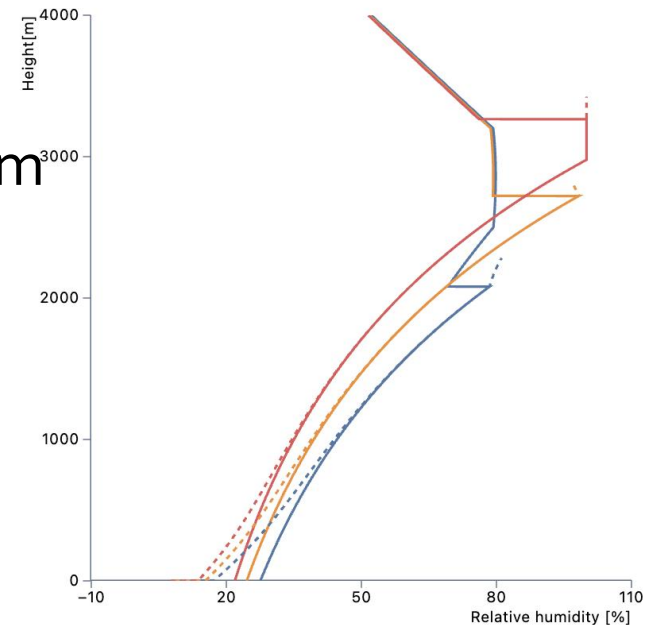


variable: vertical velocity [m/s] ▾

Time (UTC): 17:00

Vertical profiles

- ☒ Martorell simplified ☒ Martorell simplified/High H (0.25)
☒ Martorell simplified/Very high H (0.35)
- ☒ soundings/martorell/26-2021-07-13 17:05:07.csv
☒ soundings/martorell/25-2021-07-13 16:25:11.csv
☒ soundings/martorell/24-2021-07-13 16:09:22.csv



variable: Relative humidity [%] ▾

Time (UTC): 17:00

Exercise 3.3 – Discussion: Fire size

$l_{fire} \uparrow \rightarrow A_{plume} \uparrow \rightarrow \text{mixing} \downarrow \rightarrow \theta_{plume} \uparrow \rightarrow B \uparrow \rightarrow w_{plume} \uparrow \rightarrow \text{Plume top} \uparrow$

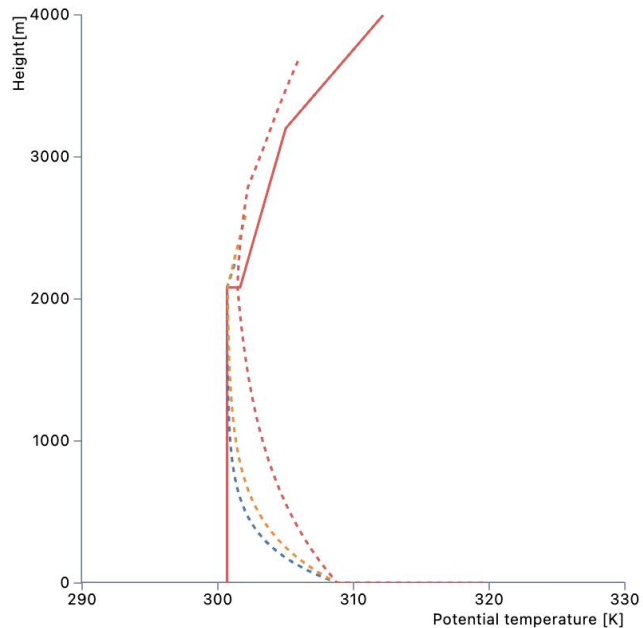
$\theta_{plume} \uparrow \rightarrow \text{initially lower RH}$

Plume top $\uparrow \rightarrow \text{plume top } T \downarrow \rightarrow RH_{top} \uparrow \text{ and condensation} \rightarrow \text{plume top} \uparrow.$

Vertical profiles

☒ Martorell simplified ☒ Martorell simplified/Larger fire
☒ Martorell simplified/Massive fire

☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv



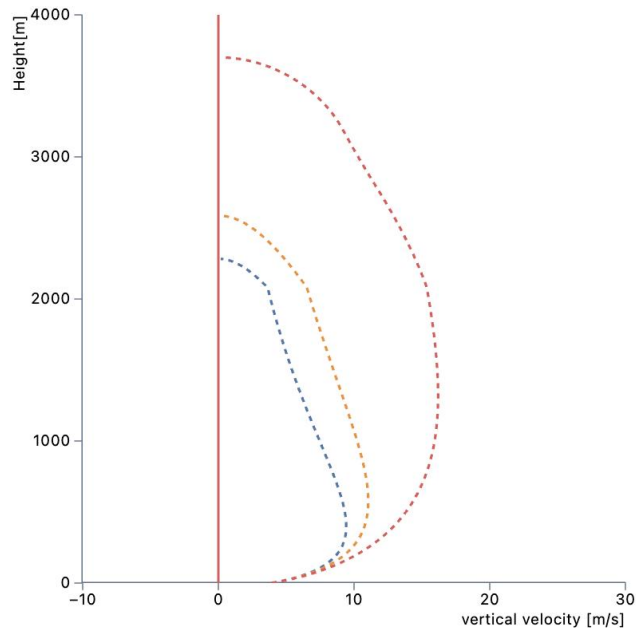
variable: Potential temperature [K] ▾

Time (UTC): 17:00

Vertical profiles

☒ Martorell simplified ☒ Martorell simplified/Larger fire
☒ Martorell simplified/Massive fire

☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv



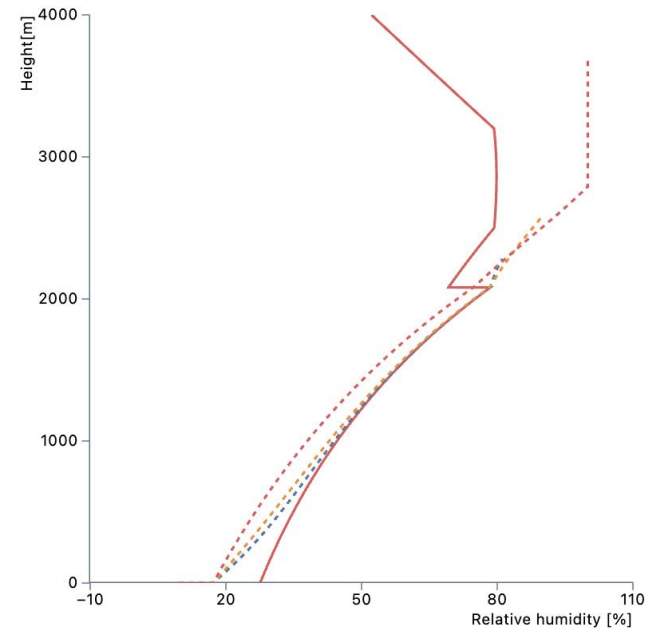
variable: vertical velocity [m/s] ▾

Time (UTC): 17:00

Vertical profiles

☒ Martorell simplified ☒ Martorell simplified/Larger fire
☒ Martorell simplified/Massive fire

☐ soundings/martorell/26-2021-07-13 17:05:07.csv
☐ soundings/martorell/25-2021-07-13 16:25:11.csv
☐ soundings/martorell/24-2021-07-13 16:09:22.csv



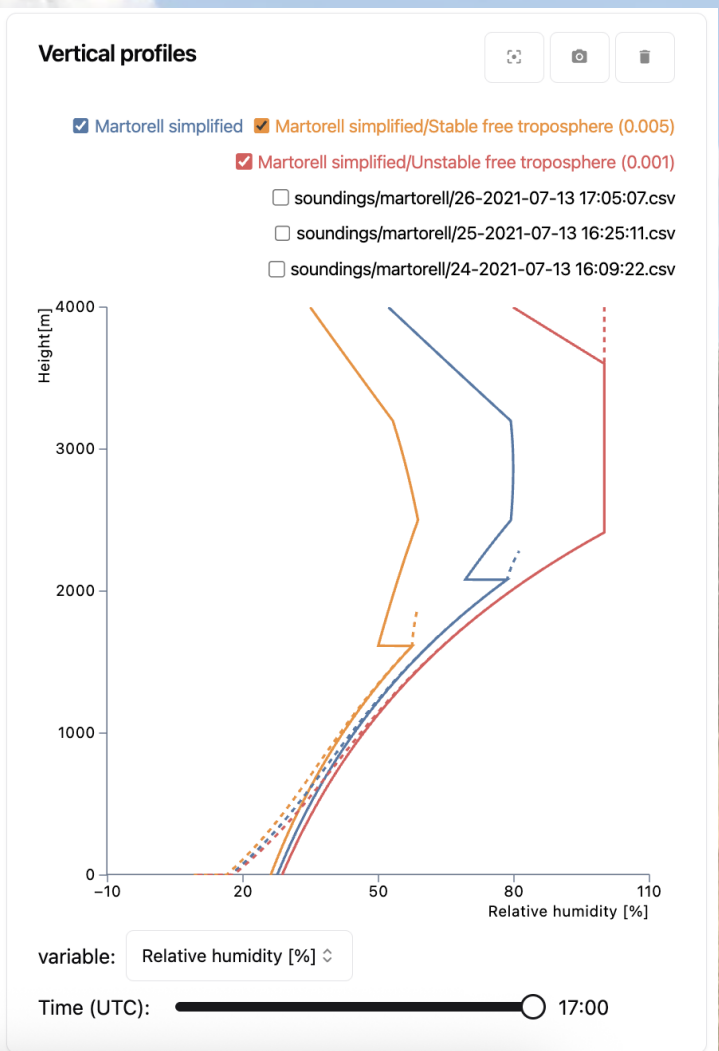
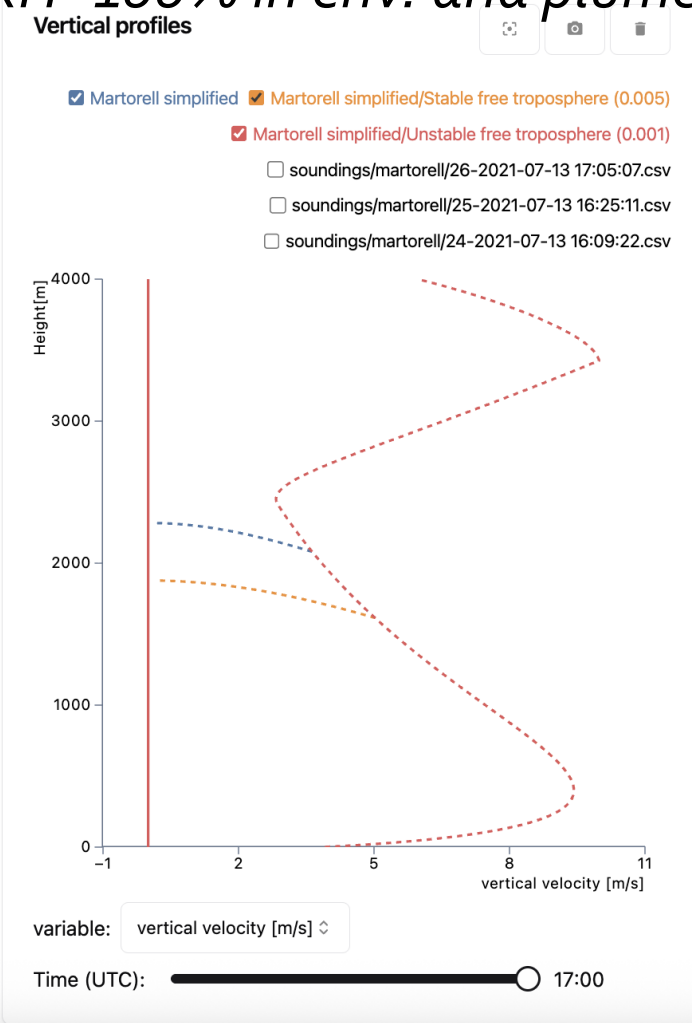
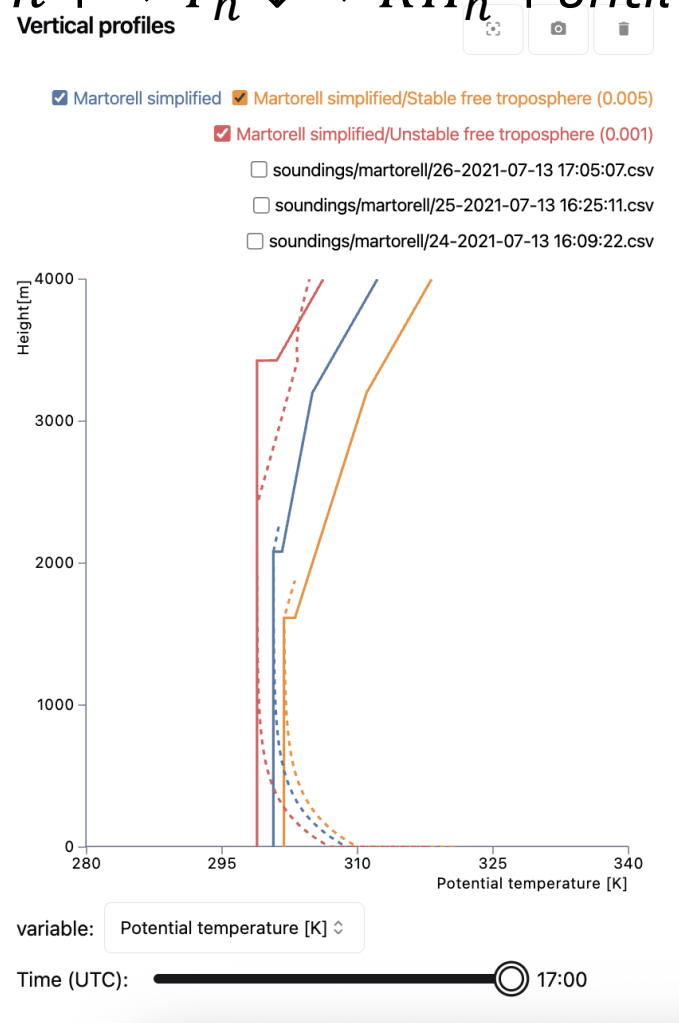
variable: Relative humidity [%] ▾

Time (UTC): 17:00

Exercise 3 – Discussion: Lapse rate

$\gamma_\theta \downarrow \rightarrow 1. \langle \theta \rangle \downarrow$ and $2. h \uparrow$
 $\langle \theta \rangle \downarrow \rightarrow \theta_{plume} \downarrow \rightarrow RH_{plume} \uparrow$
 $h \uparrow \rightarrow T_h \downarrow \rightarrow RH_h \uparrow$ until $RH=100\%$ in env. and plume.

$\Rightarrow$ Mixed layer becomes cloud-topped
 $\Rightarrow B > 0, w_{plume} \uparrow \Rightarrow$ pyrocumulus



Simple models for wildfire plumes

Martin Janssens

