# Coupled Fire-Weather Dynamics: The Interplay Between Convective Plumes, Wind Patterns, and Fire Behavior

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CAL FIRE

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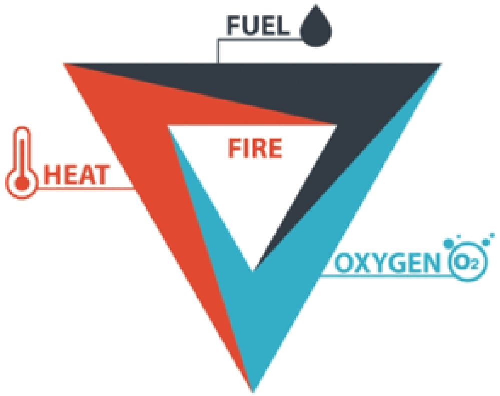
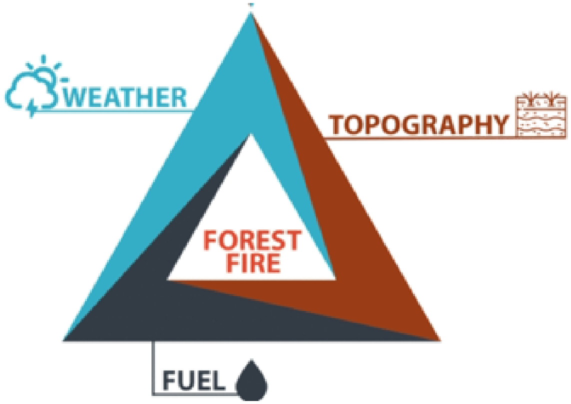
# Outline

- Fire Environment and Winds
- Coupled Fire-Atmosphere modeling
- Small-scale fire winds
- Larger-scale fire winds associated with
  - wind-driven fire
  - plume-dominated fire
- Other dynamic effects of fire on the fire environment
  - Interactions between fire and a hydraulic jump

# Fire Environment




Fire Fundamentals




Fire Environment

- **wind,**
- temperature,
- relative humidity,
- **precipitation**,
- atmospheric stability

# Primary Factors Affecting Fire Behavior

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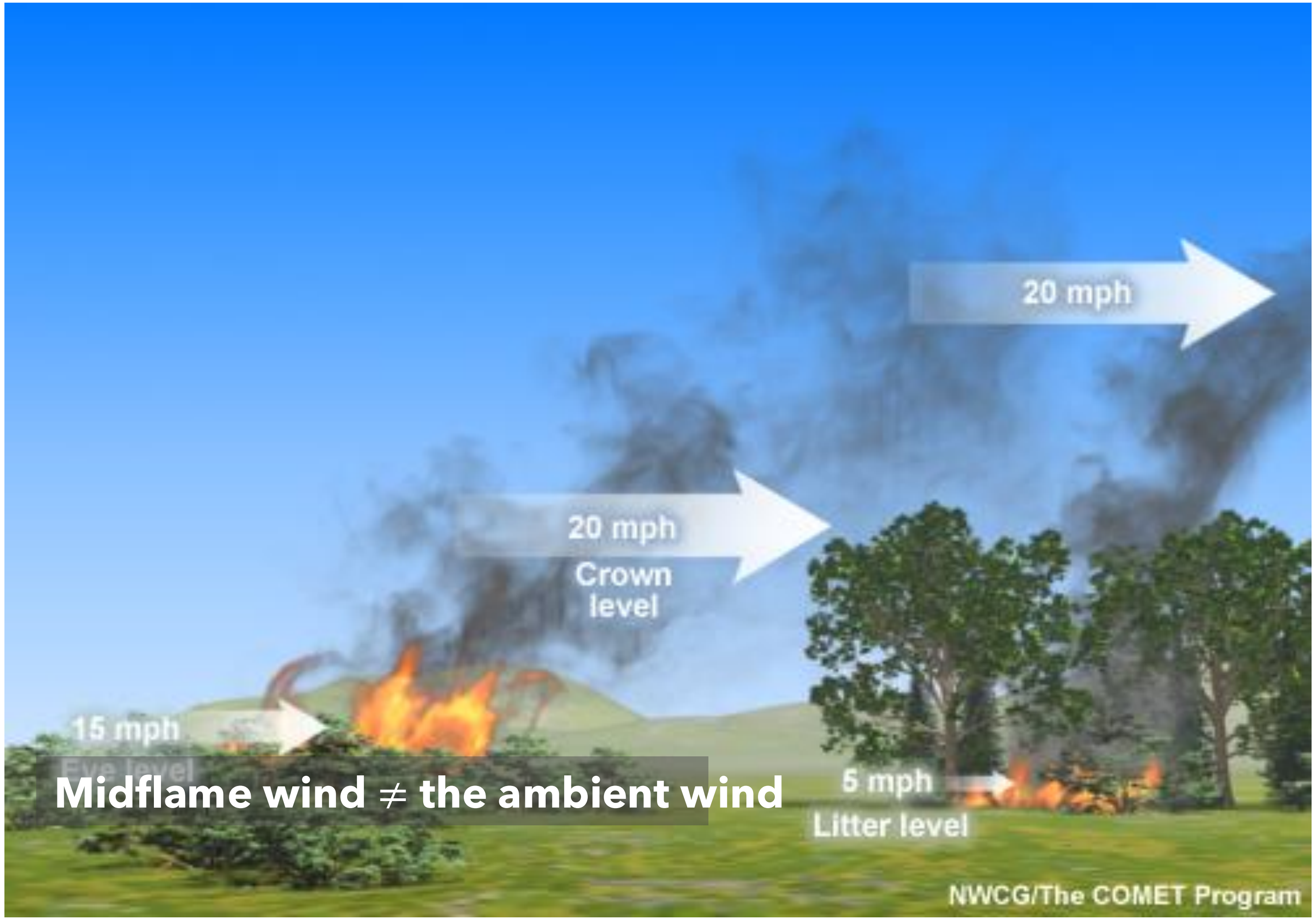
- **Wind speed**
- Steepness of slope
- Fuel type
- **Fuel moisture**

Traditionally considered as external factors

The wind interacting with the firefront is not the same as the ambient wind away from the fire

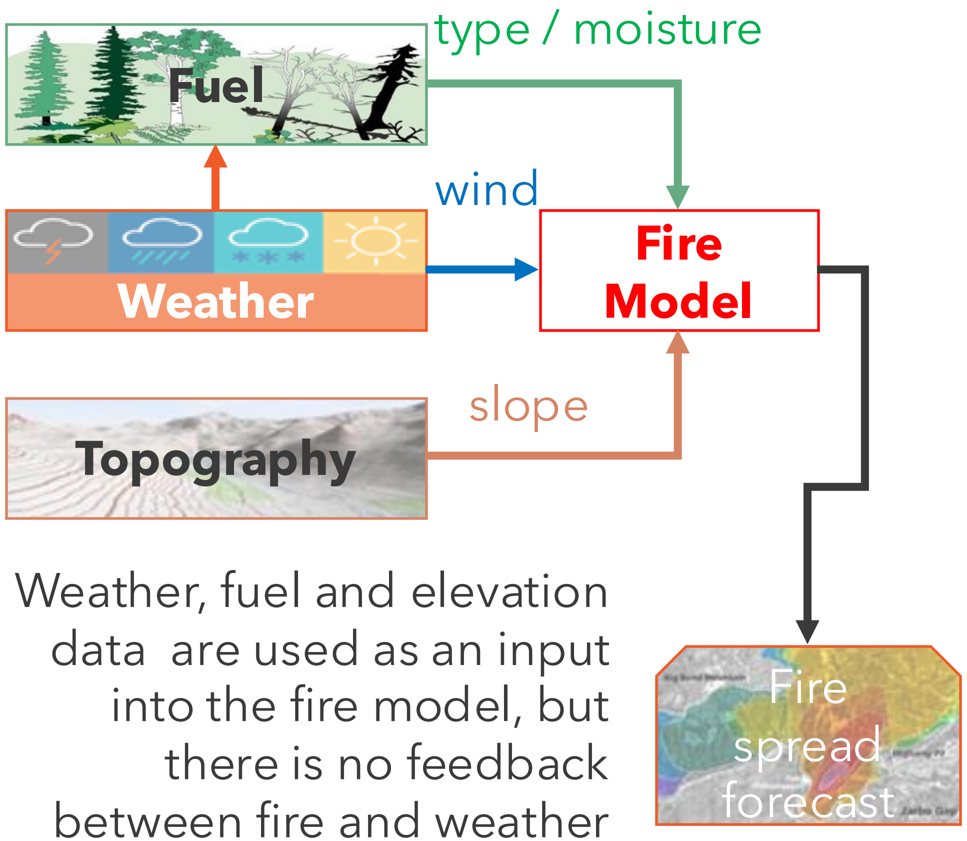
Fire can modify local weather conditions driving fire propagation

Fuel moisture can also be affected by fire activity in cases when fire induces precipitation



# Uncoupled modeling



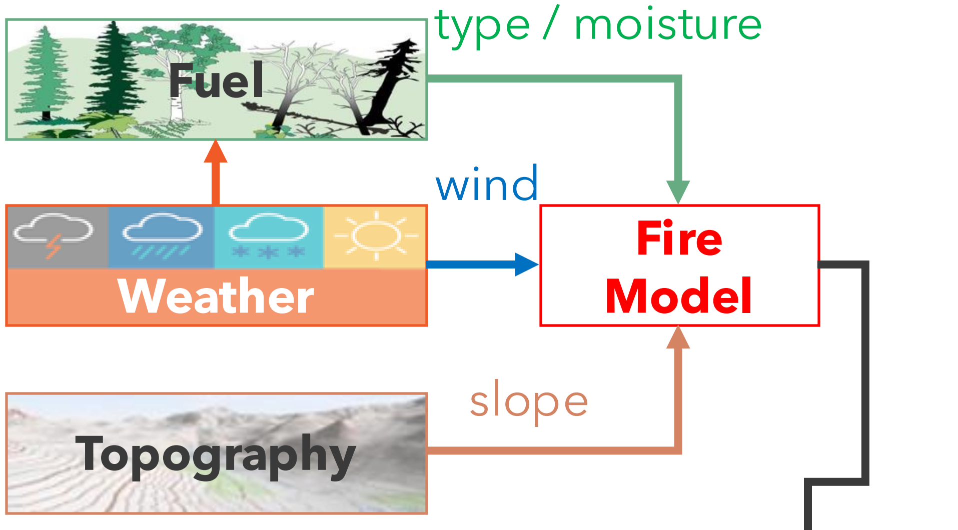



Weather, fuel and elevation data are used as an input into the fire model, but there is no feedback between fire and weather

Behave, Farsite, Prometheus, FSPro…

# Uncoupled vs. coupled modeling






Weather, fuel and elevation data are used as an input into the fire model, but there is no feedback between fire and weather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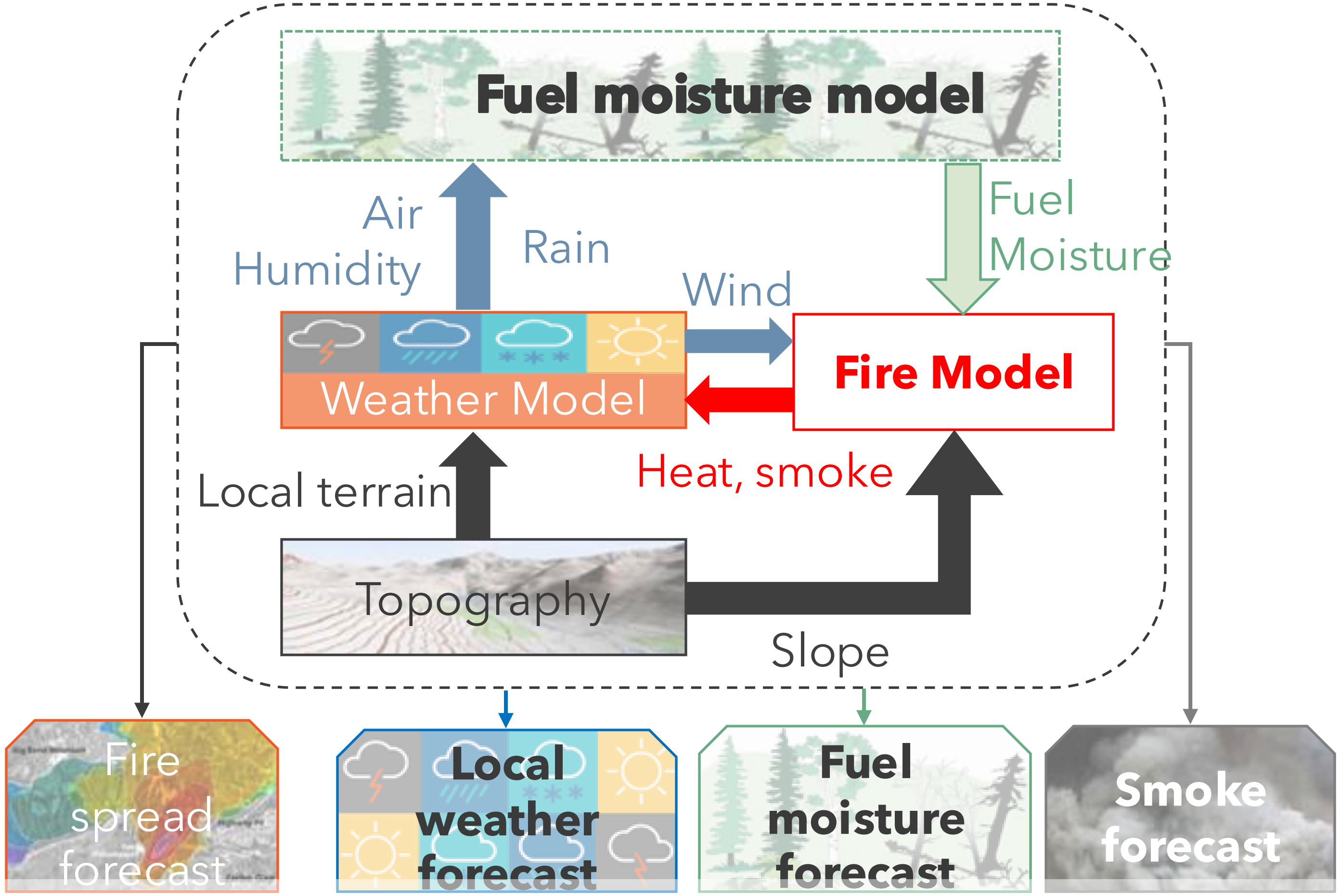
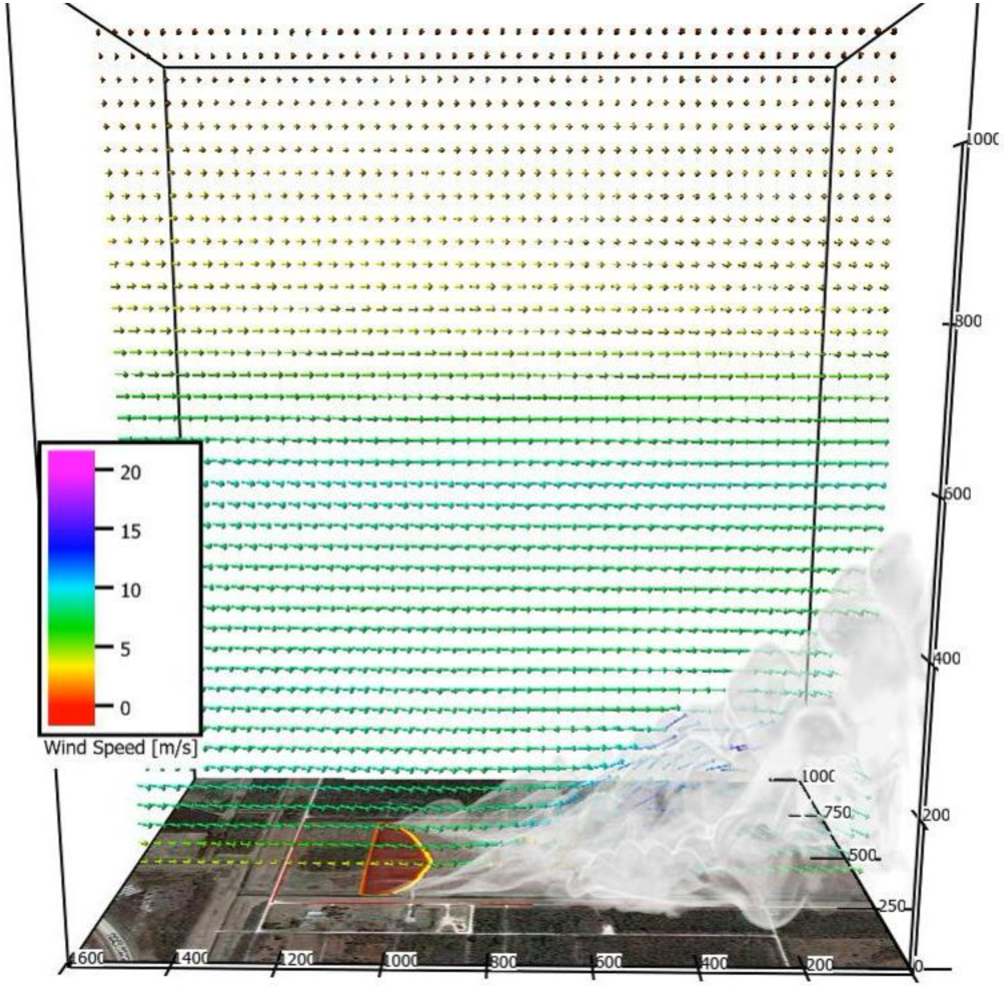
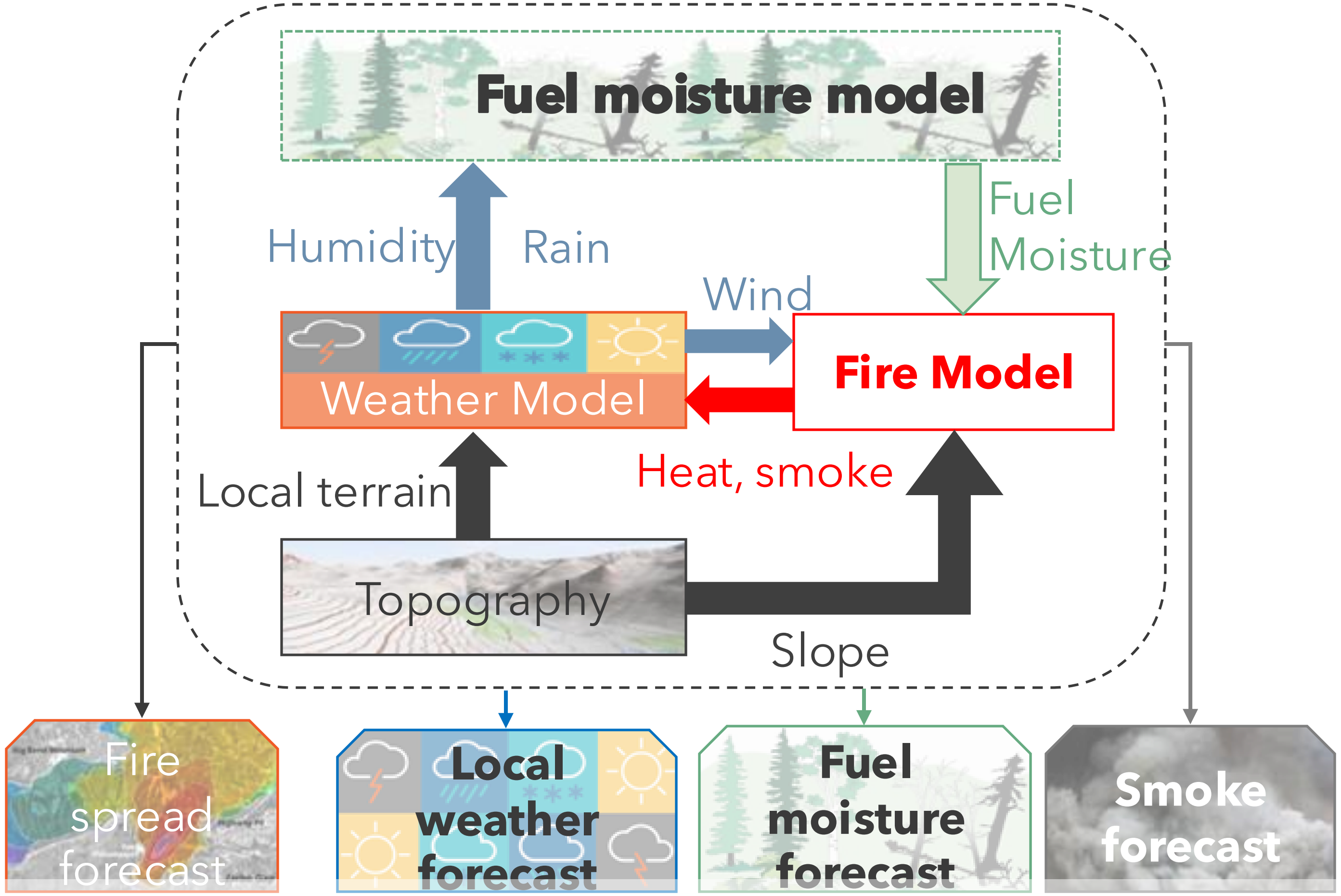



Fire itself affects local weather via heat release and smoke. Local fire-affected weather conditions drive fuel moisture and fire propagation

Fully physical: WFDS, FIRETEC, parameterized: WRF-SFIRE, CAWFEE

# Coupled modeling




Fire itself affects local weather via heat release and smoke. Local fire-affected weather conditions drive fuel moisture and fire propagation

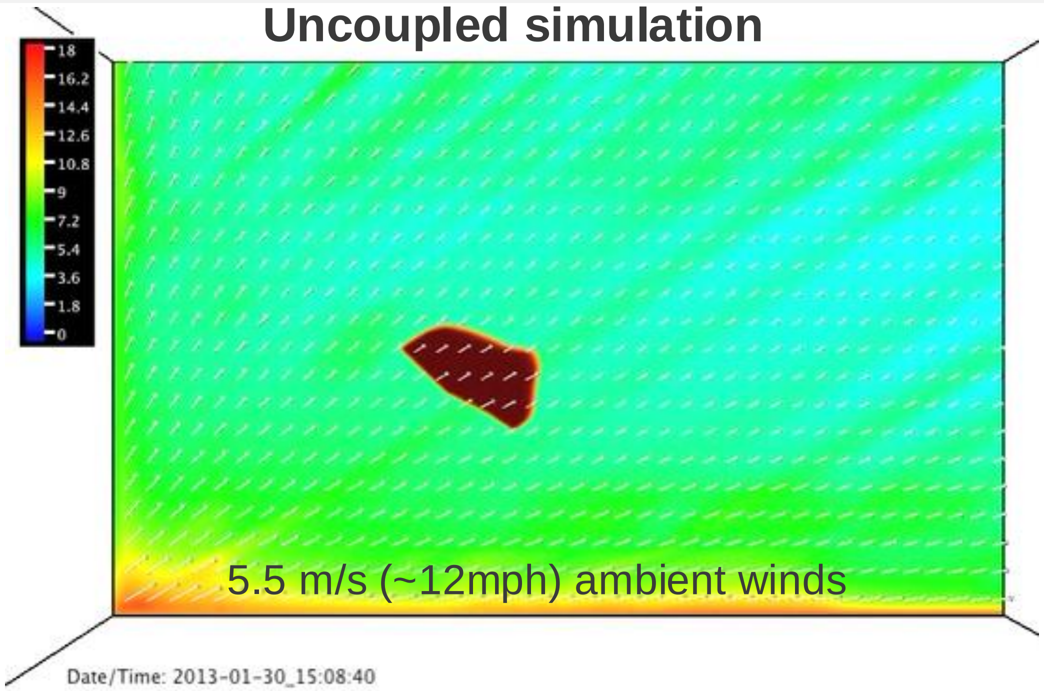
Fully physical: WFDS, FIRETEC, parameterized: WRF-SFIRE, CAWFEE

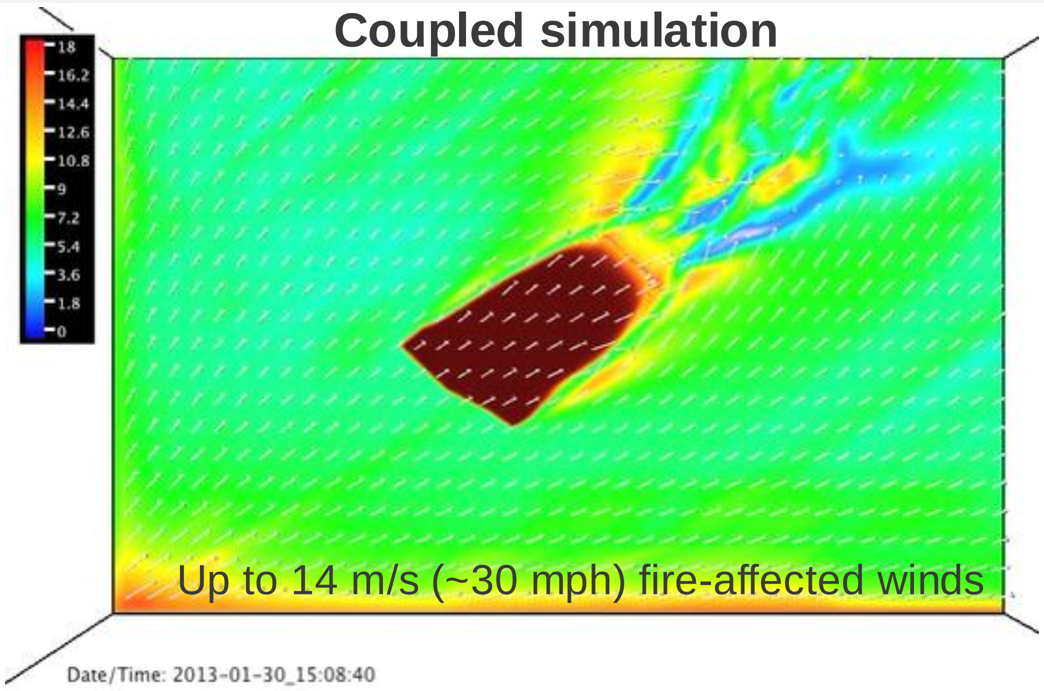
# Observations of Fire-Atmosphere Interactions



- Fire-induced winds can't be measured directly, because even the local measurements at the fire front reflect the winds already modified by the fire
- We can, however, run a set of simulations with, and without fire-atmosphere coupling (no heat from the fire released to the atmosphere) and compare them to assess fire impacts
- The difference between the coupled and non-couped simulation allows quantifying the fire effects on the fire environment **[fire winds = coupled simulation winds – uncoupled simulation winds]**

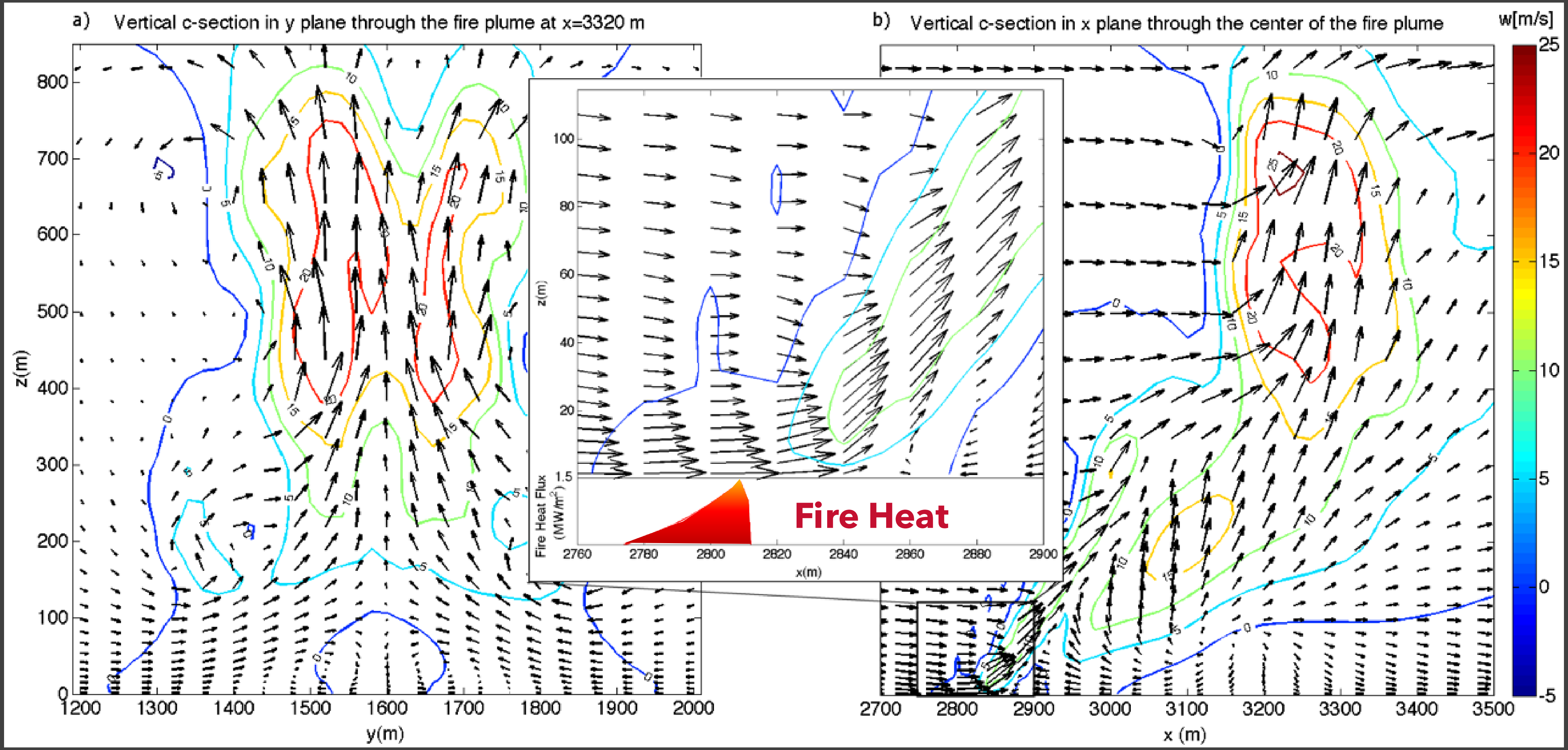
# Assessing fire-induced winds




- Fire significantly changes the surface wind pattern, winds become much more variable than in the uncoupled simulation
- The peak winds become almost three times stronger
- In the coupled simulation resolving fire-winds, the fire propagates much faster

# Small-scale mechanism of fire-induced winds




- The fire-released heat generates buoyancy and the convective updraft
- Ambient winds push the convective column ahead of the fire front
- The inflow into the base of the convective column generates cross-fire winds

# Small-scale mechanism of fire-induced winds

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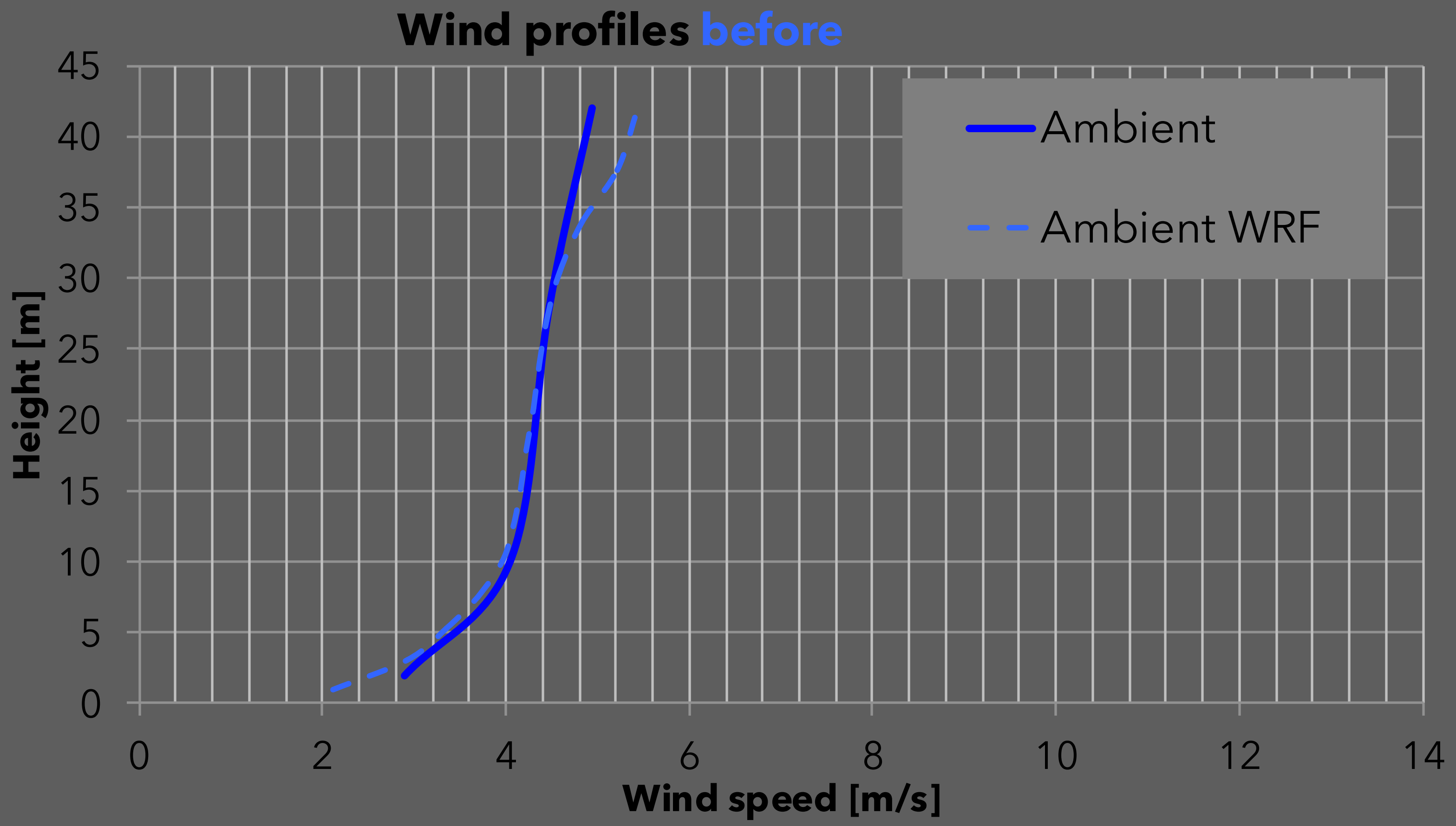


- Away from the fire, the winds increase logarithmically with height

# Small-scale mechanism of fire-induced winds

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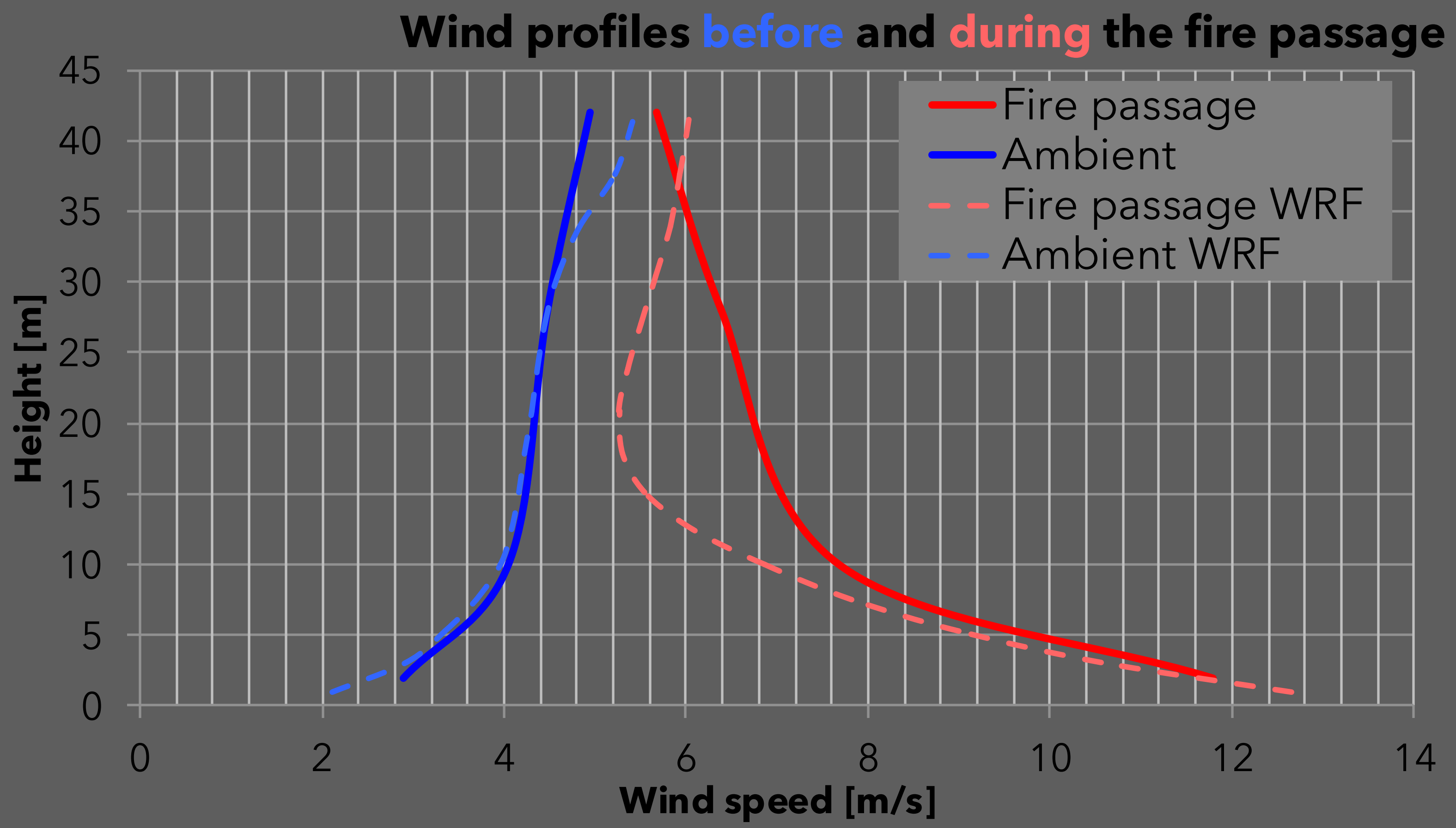
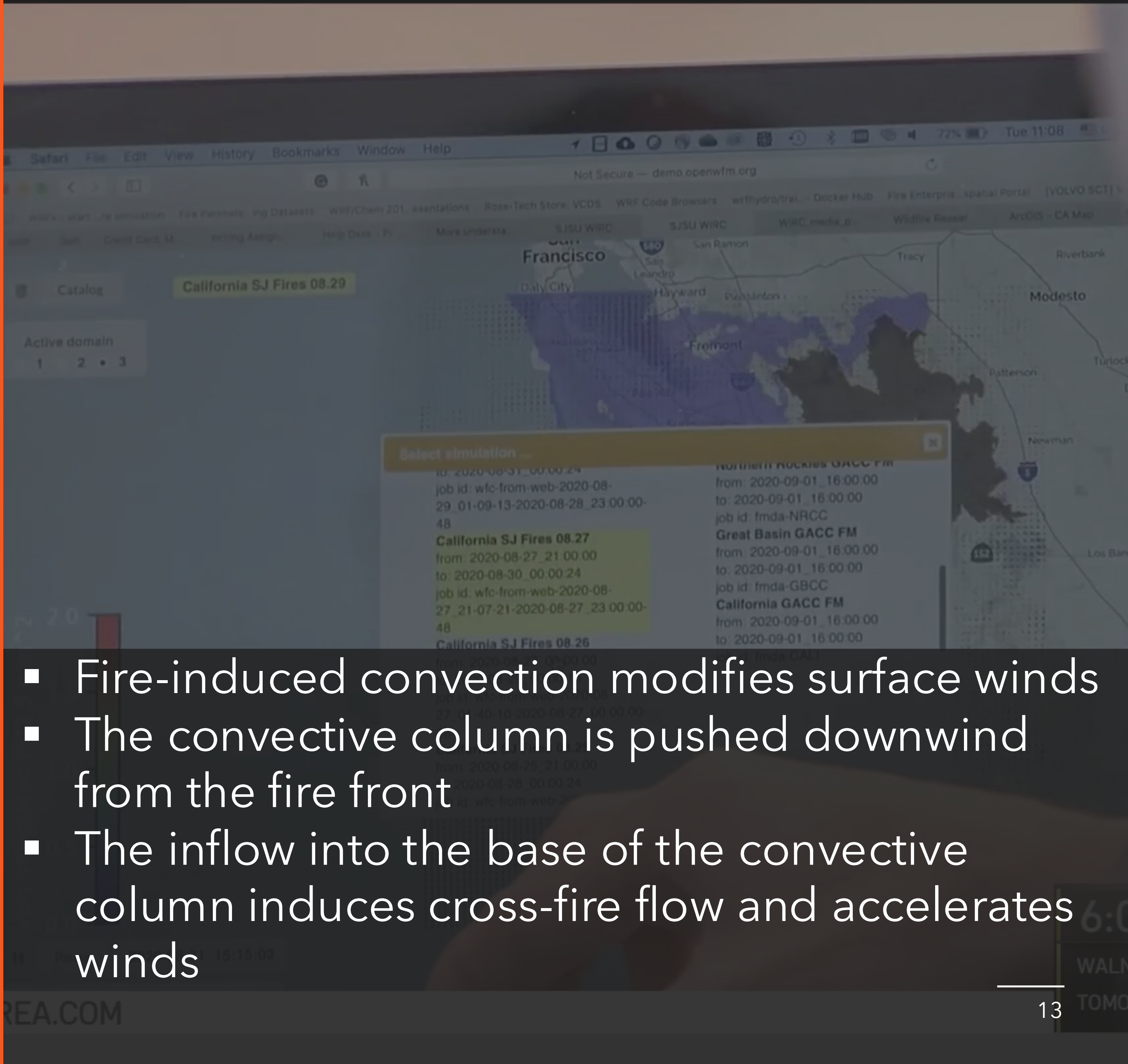


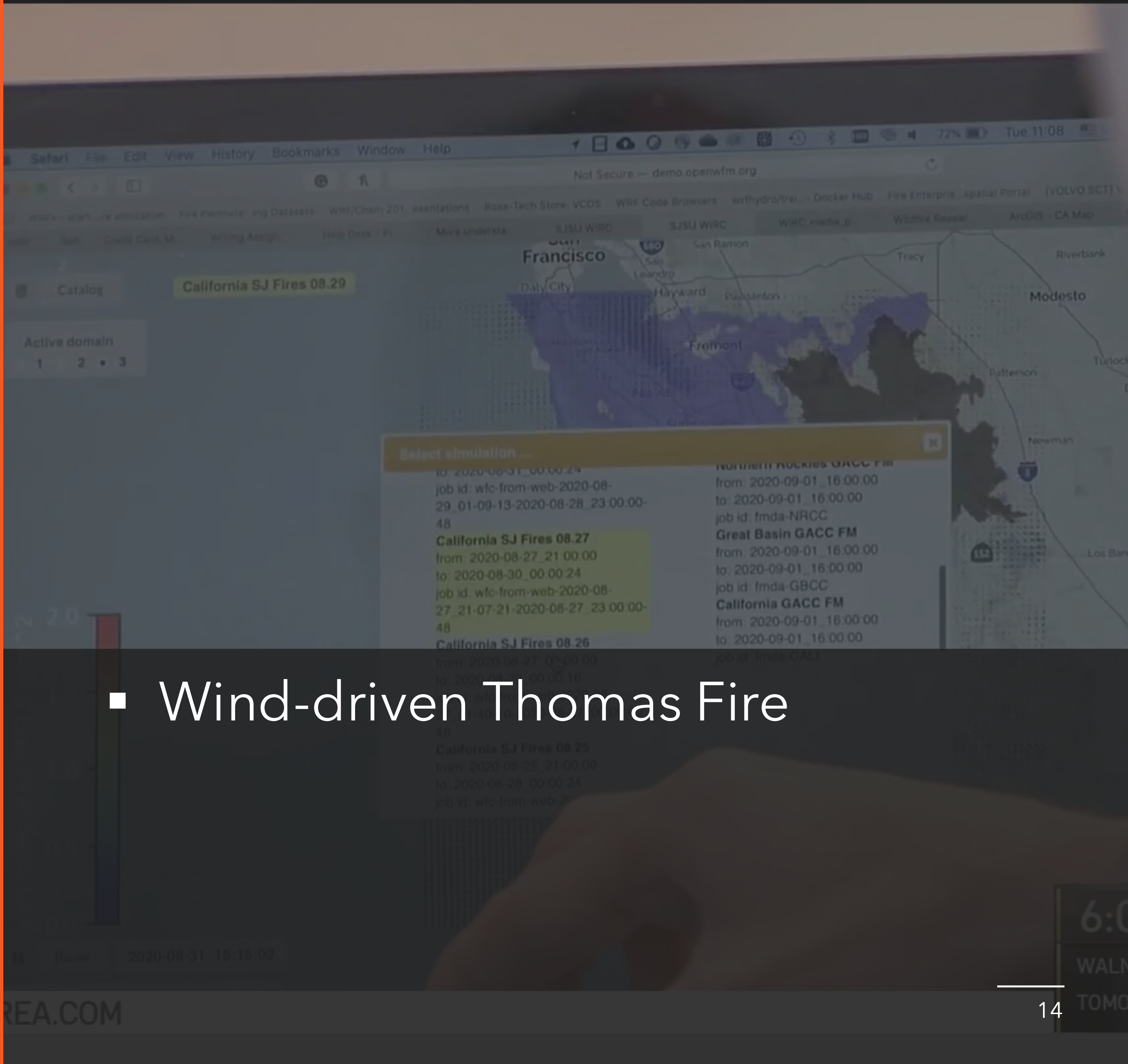

- Away from the fire, the winds increase logarithmically with height
- During the fire front passage the wind profile dramatically changes
- The winds accelerate near the surface and become stronger than aloft

# Fire winds at small scales




- Fire-induced convection modifies surface winds
- The convective column is pushed downwind from the fire front
- The inflow into the base of the convective column induces cross-fire flow and accelerates winds

# Fire winds at larger scales




- Wind-driven Thomas Fire

# Wind-Driven Fire (Thomas)


Started on December 4, 2017, in Ventura County, and eventually spread into Santa Barbara County. One of the largest wildfires in California's history at the time, fueled by strong Santa Ana winds and extremely dry conditions.

Here are some key facts about the Thomas Fire:

- **Area burned**: The fire scorched **281,893 acres**
- **Containment**: The fire was fully contained on January 12, 2018, after burning for over a month.
- **Damage**: The fire destroyed over **1,000 structures**, including homes, and damaged hundreds more.

# Wind-Driven Fire (Thomas)

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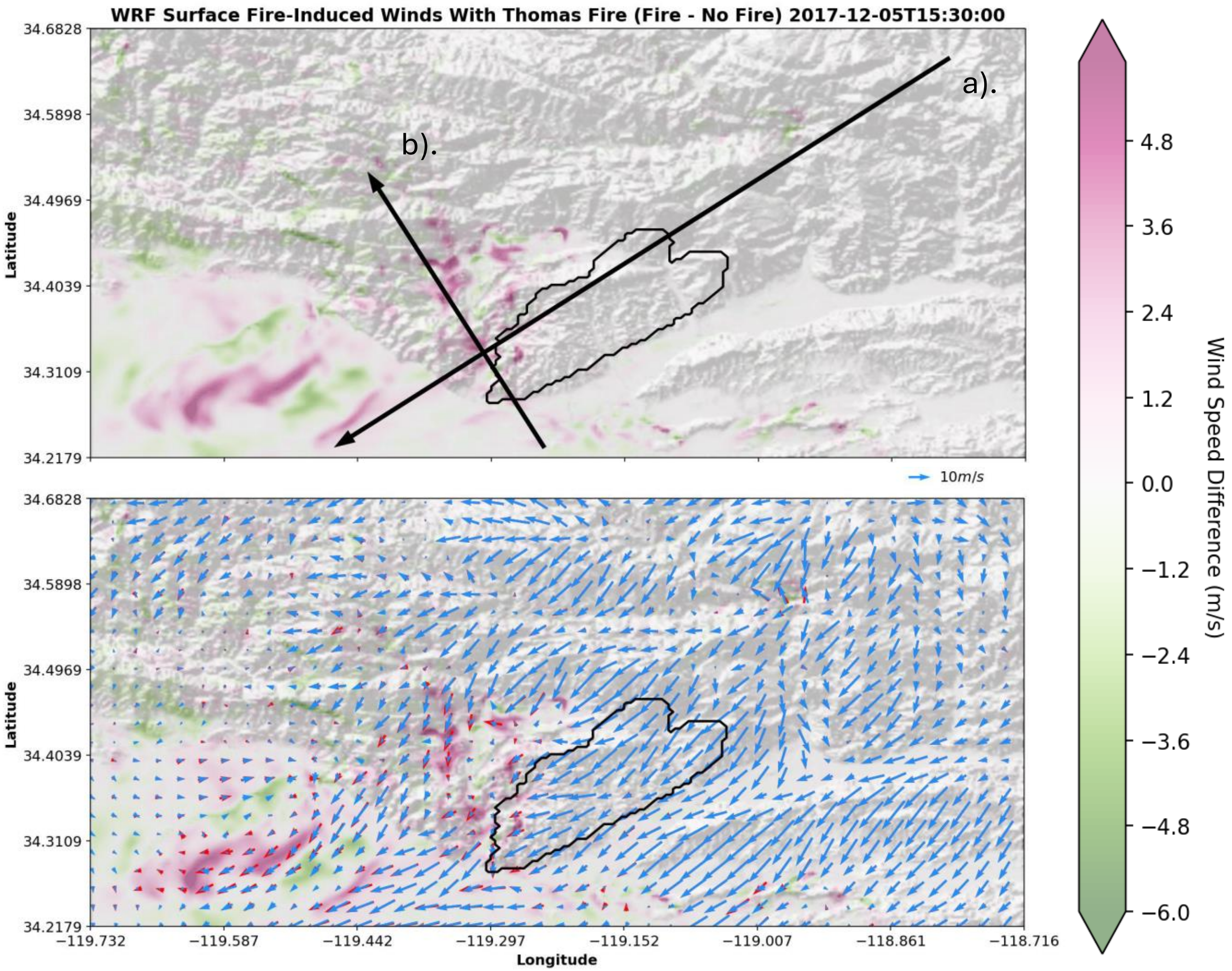
We computed the difference between the winds from coupled and uncoupled simulations, to investigate fire-induced winds.

- In this wind-driven fire even though there was no classical vertical plume that would support the notion of the chimney effect, the fire-induced winds were significant
- The spatial map indicates that the fire impacts on the wind speed under strong wind conditions have nonlocal effects
- Wind direction remains largely unchanged
- The wind field modification is mostly evident downwind from the fire, but not only there
- The wind acceleration zones ahead of the firefront have huge implications in the context of the evolution of potential spot fires

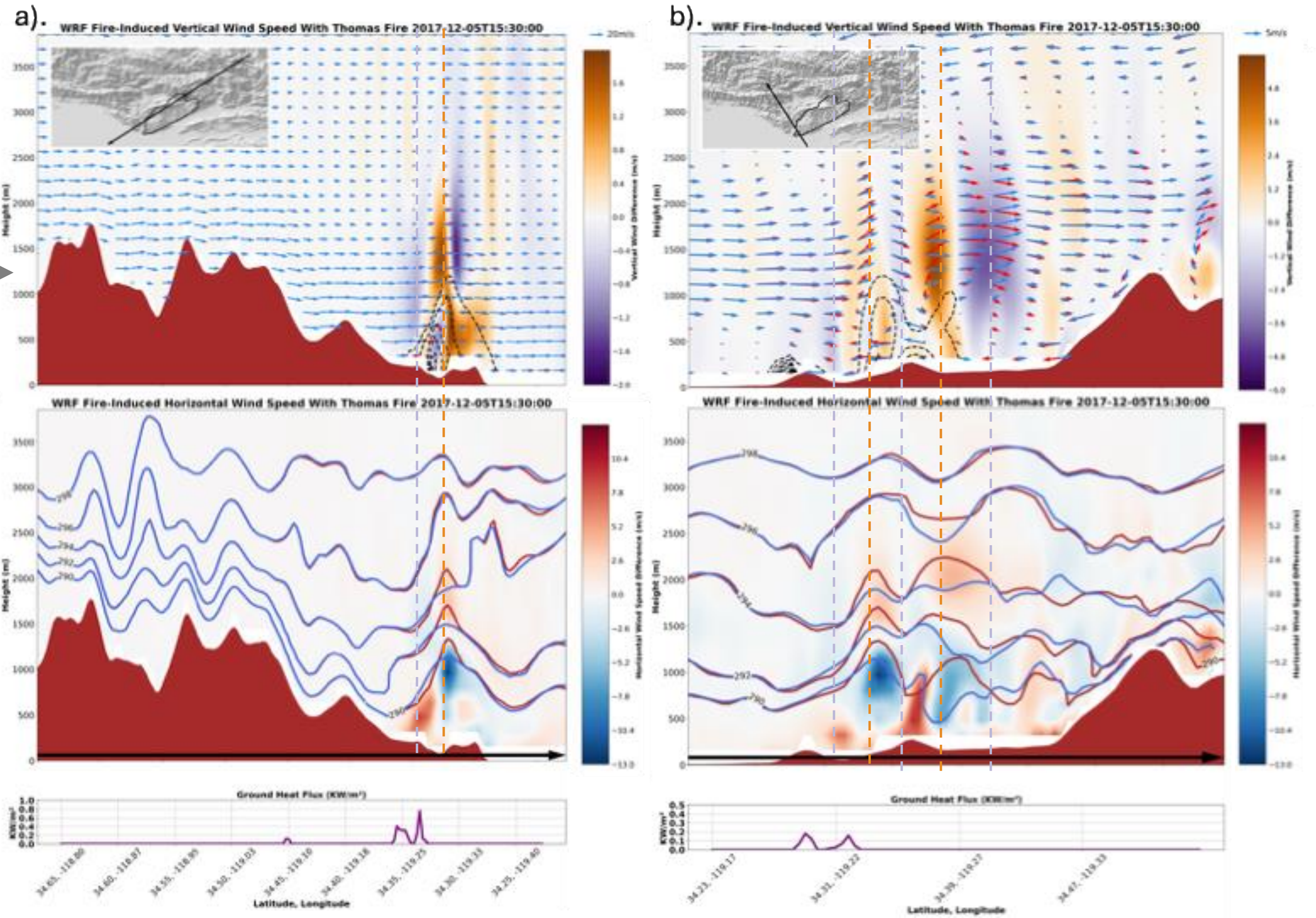


# Wind-Driven Fire (Thomas)



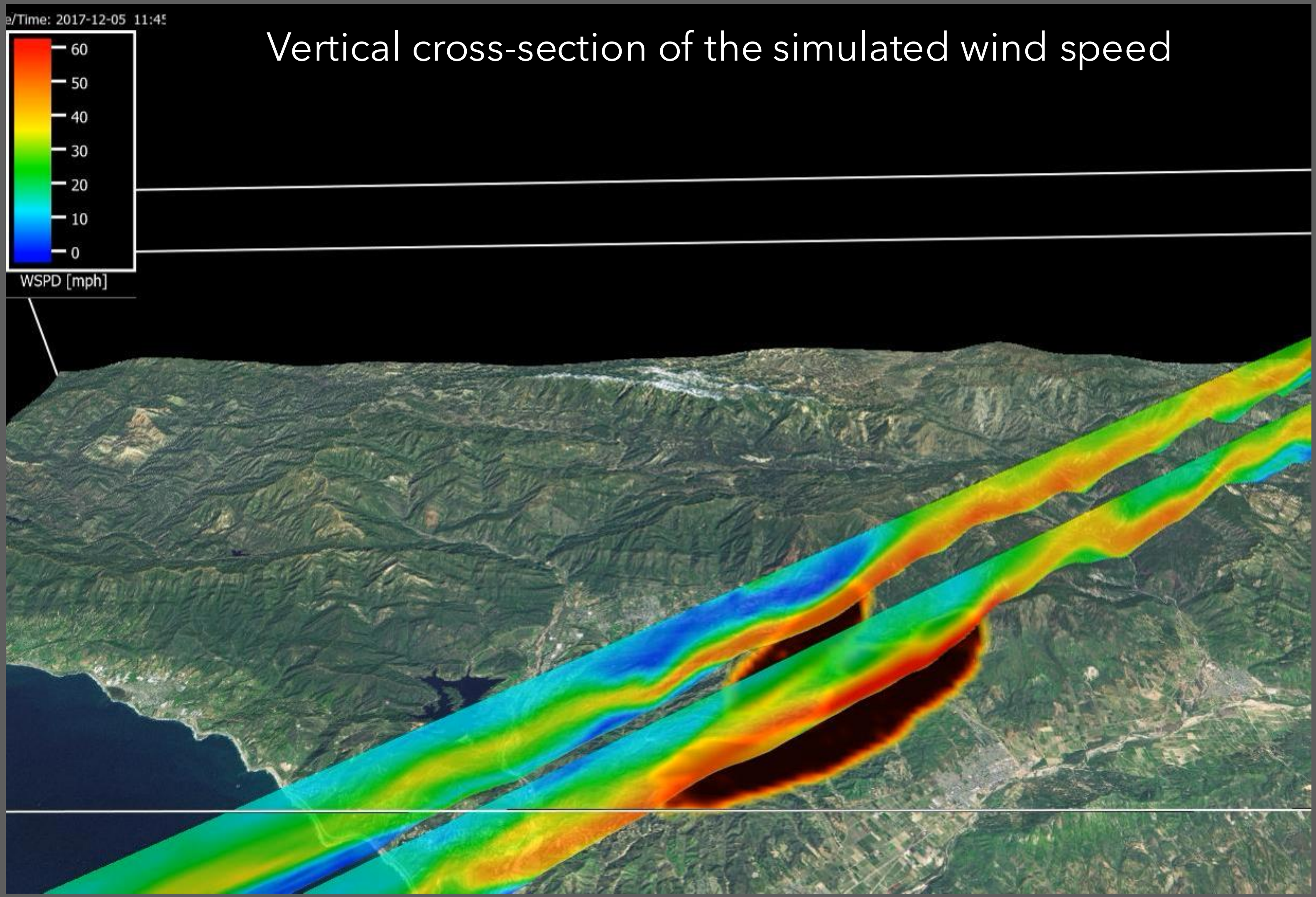
The mechanism of fire-winds during the wind-driven fire

- The fire although driven by strong winds, induces significant perturbation in the vertical velocity field
- This disturbance affects the gravity wave and results in a series of **downdraft** and **updraft** perturbations
- The downdraft zones deepen the gravity wave and bring faster winds from upper elevations down to the ground, **accelerating** near-surface winds
- The wave disturbance propagates through the atmosphere leading to non-local wind effects – acceleration and deceleration zones away from the fire



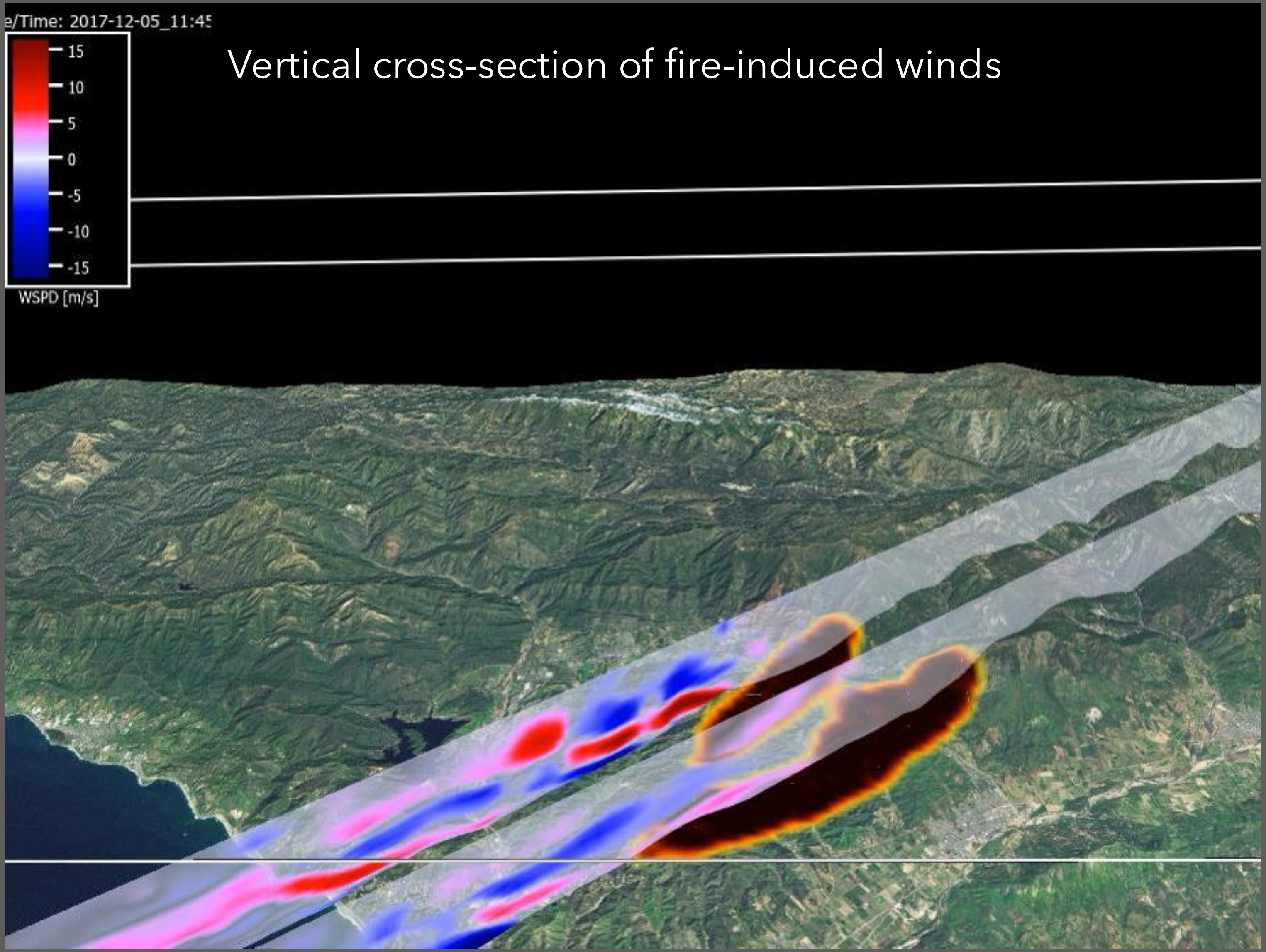
# Wind-Driven Fire (Thomas)

- Significant wave activity associated with the wind event
- Surface winds are driven by the evolution of the gravity wave



# Wind-Driven Fire (Thomas)

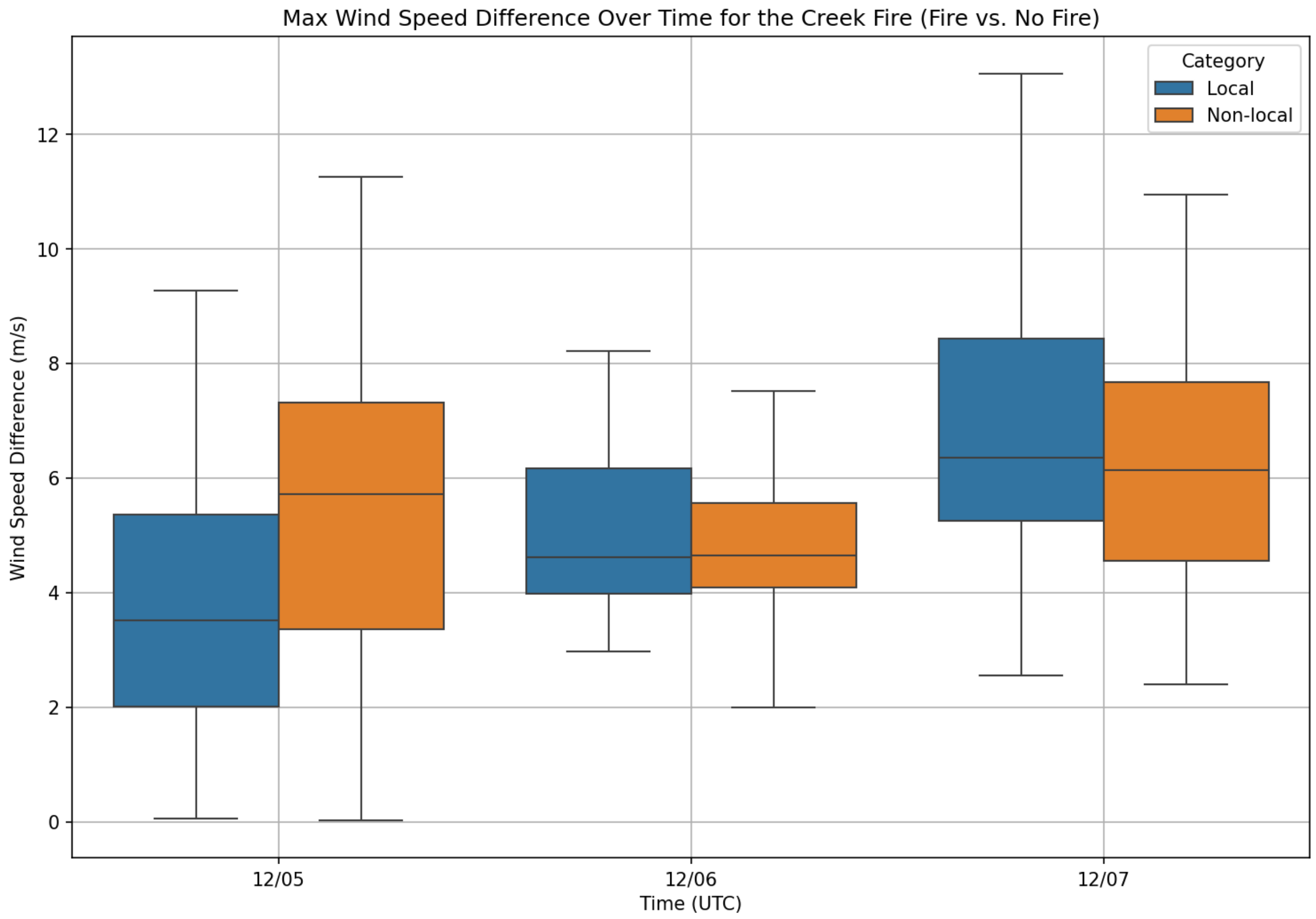
- The fire modifies winds at large distances away from the fire
- The complex pattern of wind acceleration and deceleration zones form downwind from the fire front
- Significant acceleration of winds downwind from the fire may be critical in the context of propagation of spot fires



# Wind-Driven Fire (Thomas)

To investigate the local and non-local fire effects we computed the fire-induced wind perturbation within 5km from the fire (Local) and away from this region (Non-local)

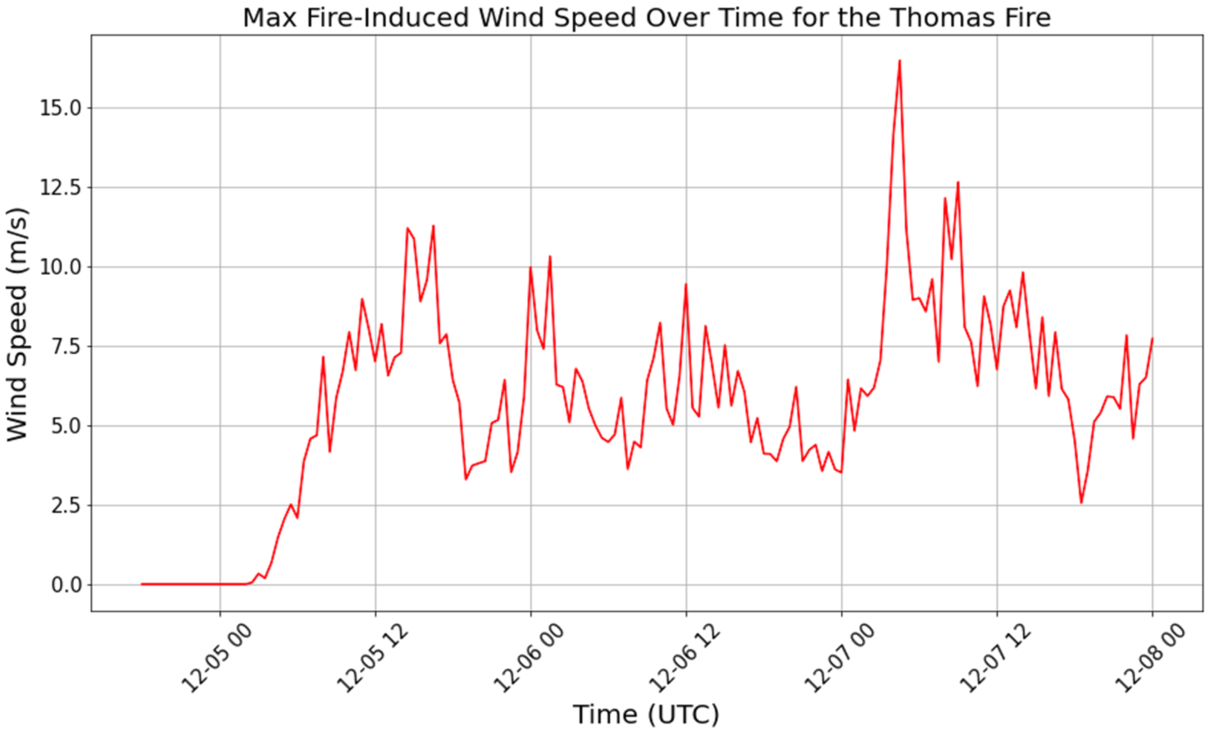
- During the initial rapid fire growth under very strong Santa Ana winds the magnitude of the non-local fire winds is significantly higher than local ones.



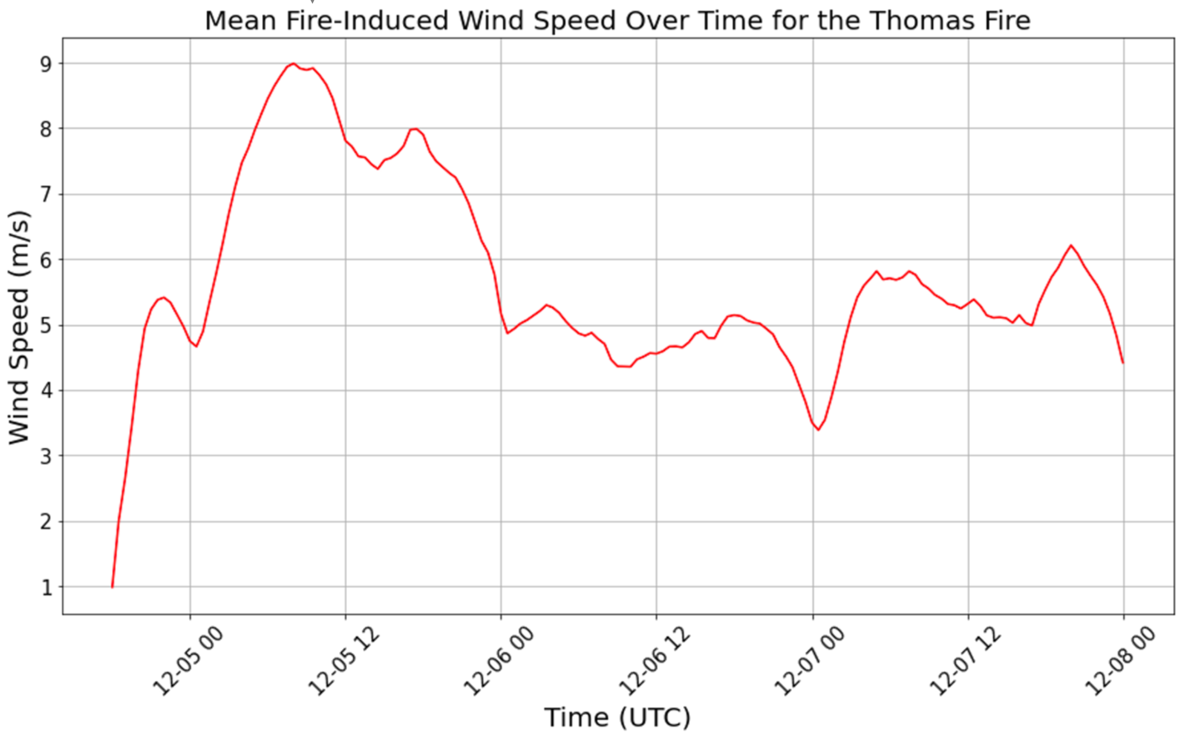
# Wind-Driven Fire (Thomas)

- The fire-induced winds are as fast as 15 m/s (34 mph!)
- The peak strength of the fire winds increases during initial fire growth and remains at relatively high levels
- On average though the fire-induced winds are strongest during the most active initial fire growth

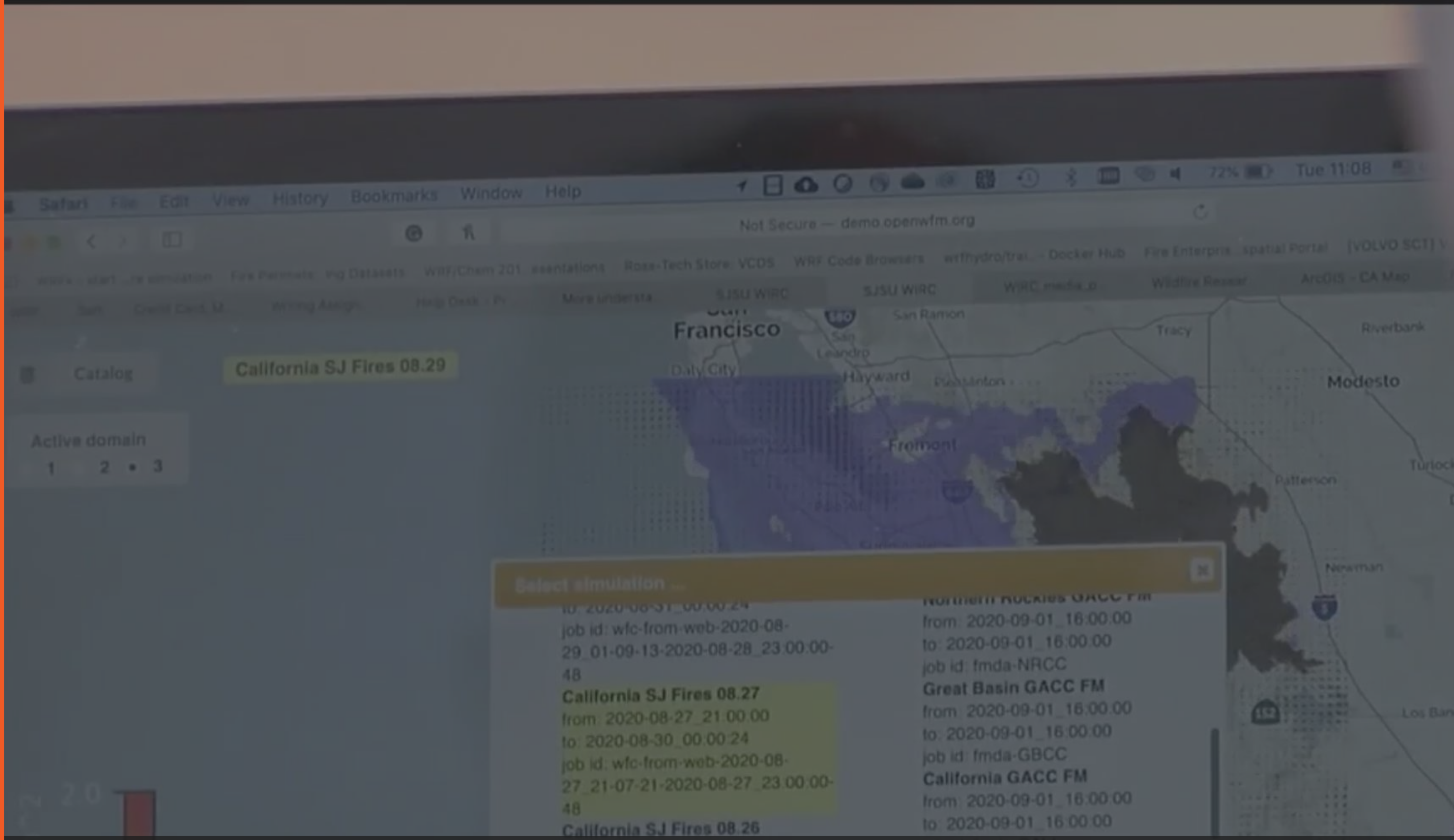
a).




b).



# Fire winds at larger scales

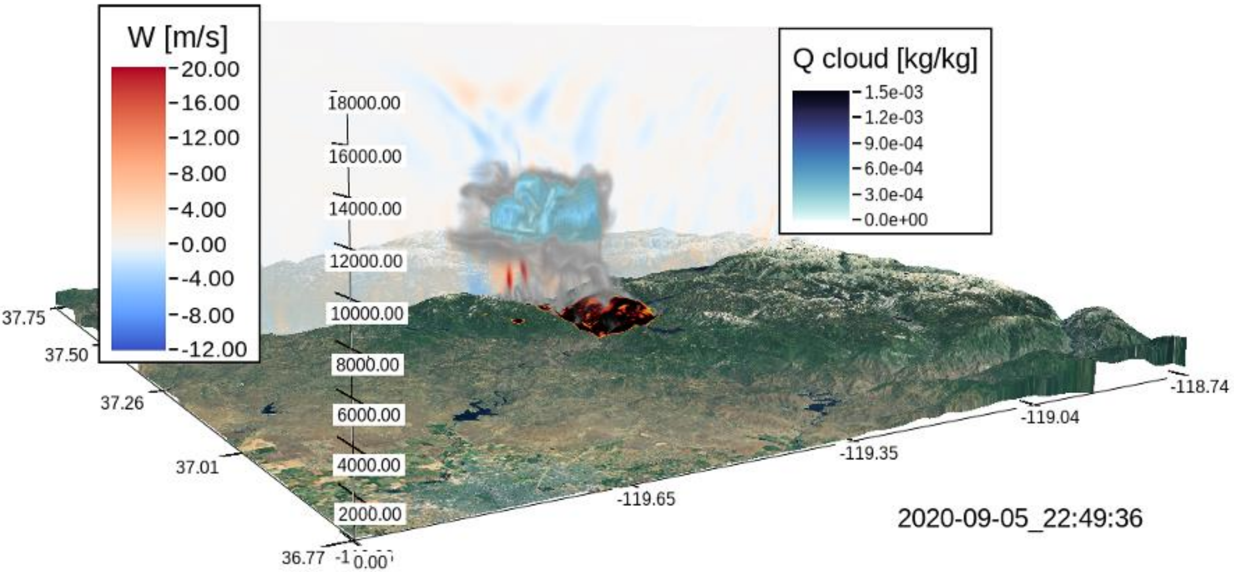



- Wind-driven Thomas Fire
  - Very strong fire winds (over 30 mph)
  - Strong non-local effects important in the context of spot fires
  - Fire winds associated with the perturbation of the gravity wave driving the wind event

# Fire winds at larger scales

- Plume-dominated Creek Fire

# Plume-Dominated Fire (Creek Fire)




- Well-developed pyroconvective column
- Blue shading shows the PyroCb formed at the top of the smoke column
- The red color on the cross-section shows the updraft cores with the vertical velocities reaching 20 m/s (44 mph)

A major wildfire that erupted in central California on September 4, 2020. It was one of the largest wildfires in California's history and caused significant destruction in the Sierra National Forest, particularly in Fresno and Madera counties.

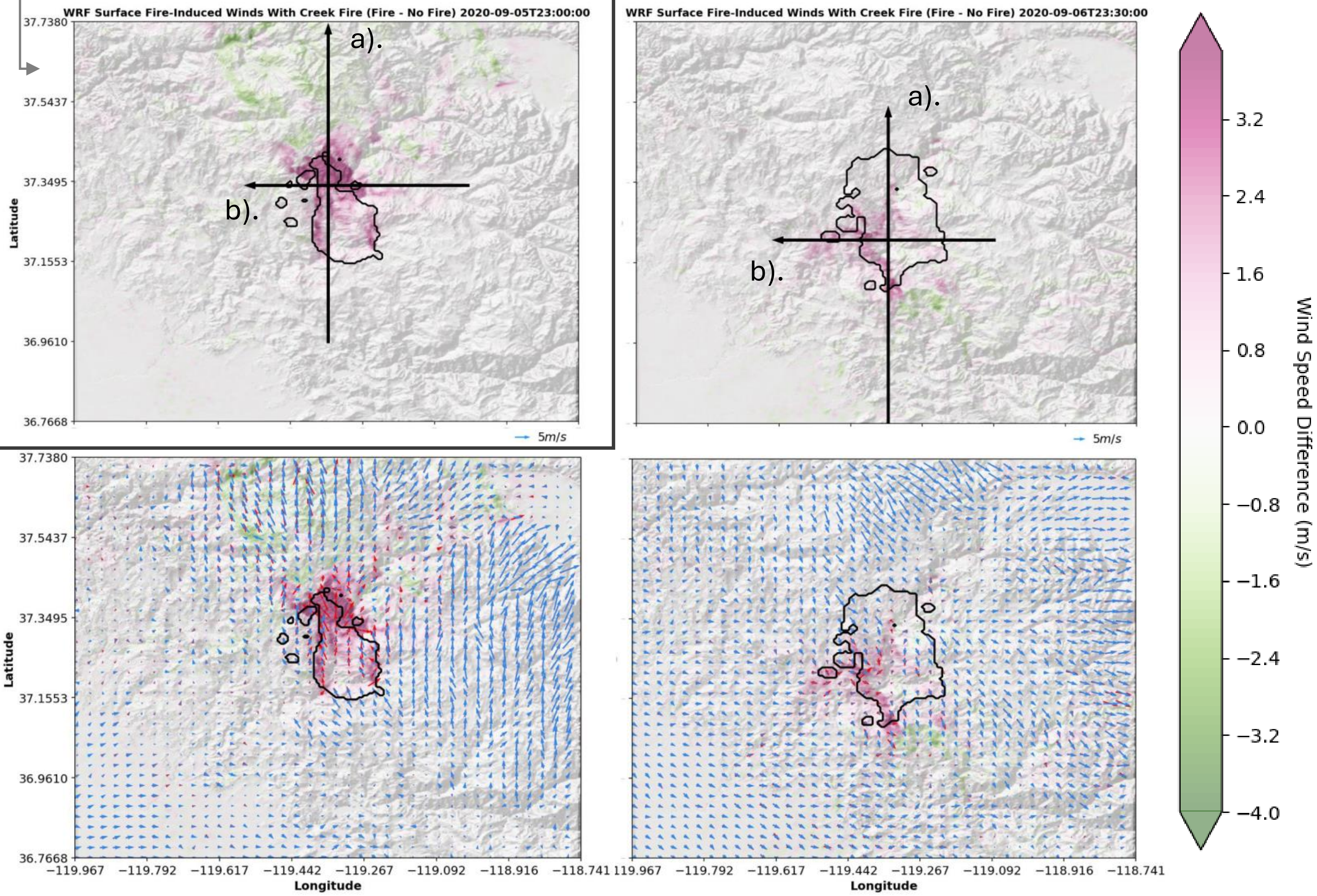
Here are some key facts about the Creek Fire:

- **Area burned**: The fire burned a total of **379,895 acres** (approximately 594 square miles), making it one of the largest single wildfires in California's recorded history.
- **Containment**: The fire was fully contained on December 24, 2020, after burning for more than three months.
- **Damage**: The Creek Fire destroyed over **850 structures**, including homes and cabins, and threatened many communities in the Sierra Nevada foothills.

# Plume-Dominated Fire (Creek Fire)

The fire grew initially under moderate winds (10 mph)
Then the winds calmed down and the fire became **plume-dominated**

- Initial stage – nonlocal effects visible but mostly wind speed reduction downwind
- Later, better-organized acceleration zones near the firefront




The initial stage under moderate winds   The subsequent stage under weak winds

# Plume-Dominated Fire (Creek Fire)

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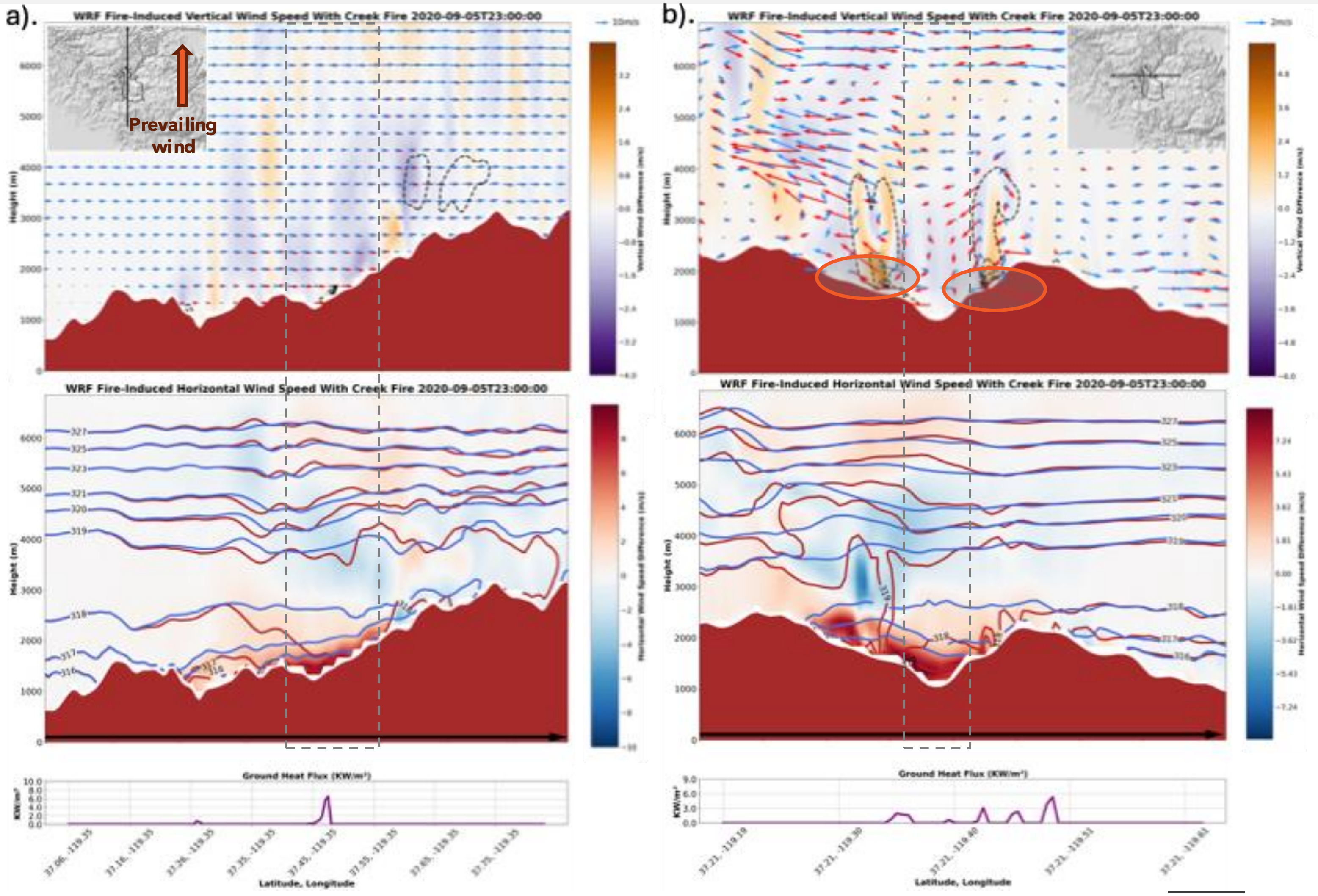
The mechanism of fire-winds during the initial stage

- Stronger heating effects from the fire and more intense updrafts than during the wind-driven fire
- Regions of fire-induced downdraft correspond to the location of wind acceleration zones
- Inflow into the base of the pyroconvective column seems to be responsible for accelerating winds in the vicinity of the fire
- Local **wind reversal** near the plume base



# Plume-Dominated Fire (Creek Fire)

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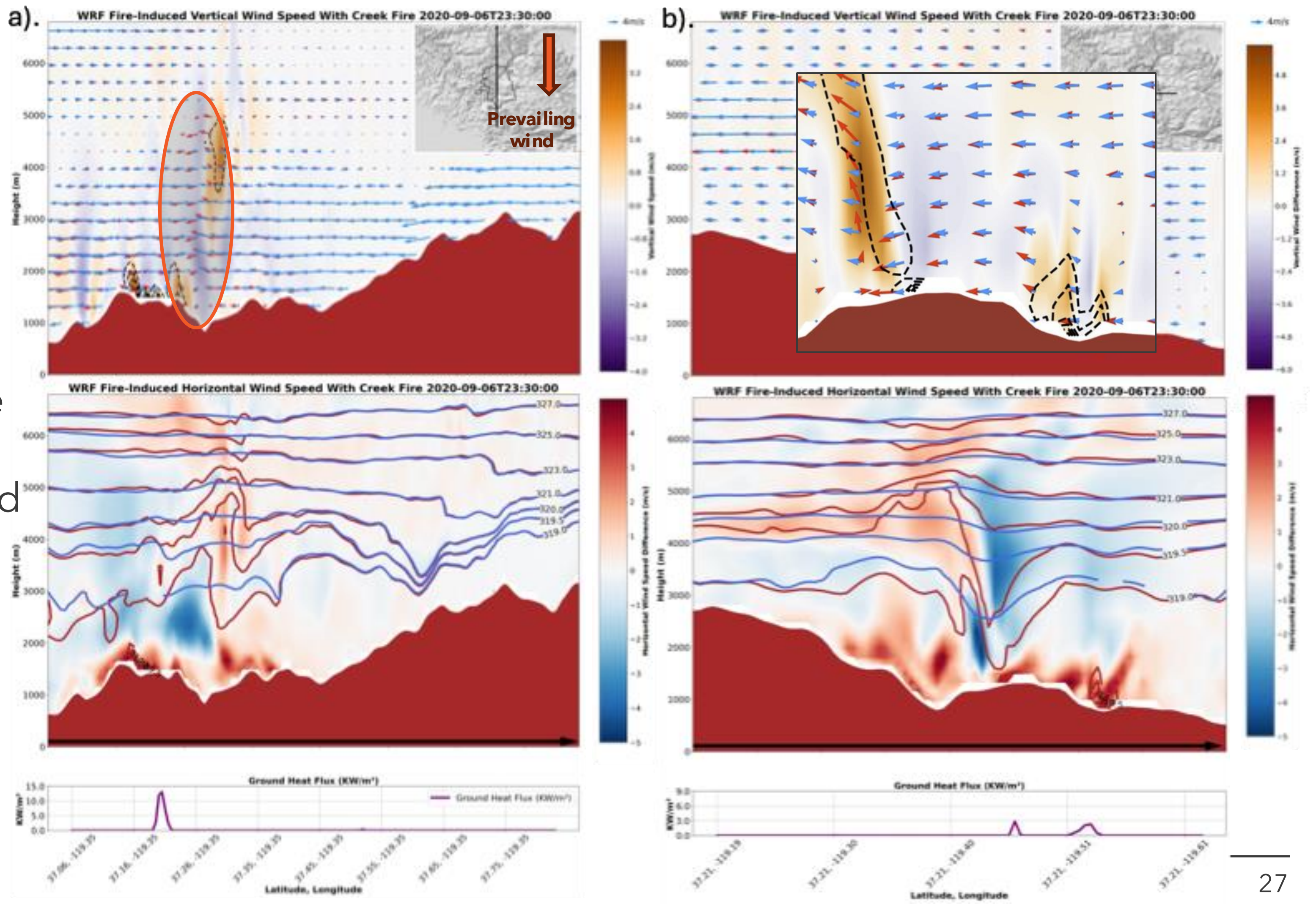
The mechanism of fire-winds during the initial stage

- The fire-induced circulation dominates the local flow pattern
- Well-defined updraft zones
- Inflow into the base of the pyroconvective column modifies the fire environment accelerating winds
- Fire-winds have more local character and are confined mostly to the regions near the active fire



# Plume-Dominated Fire (Creek Fire)

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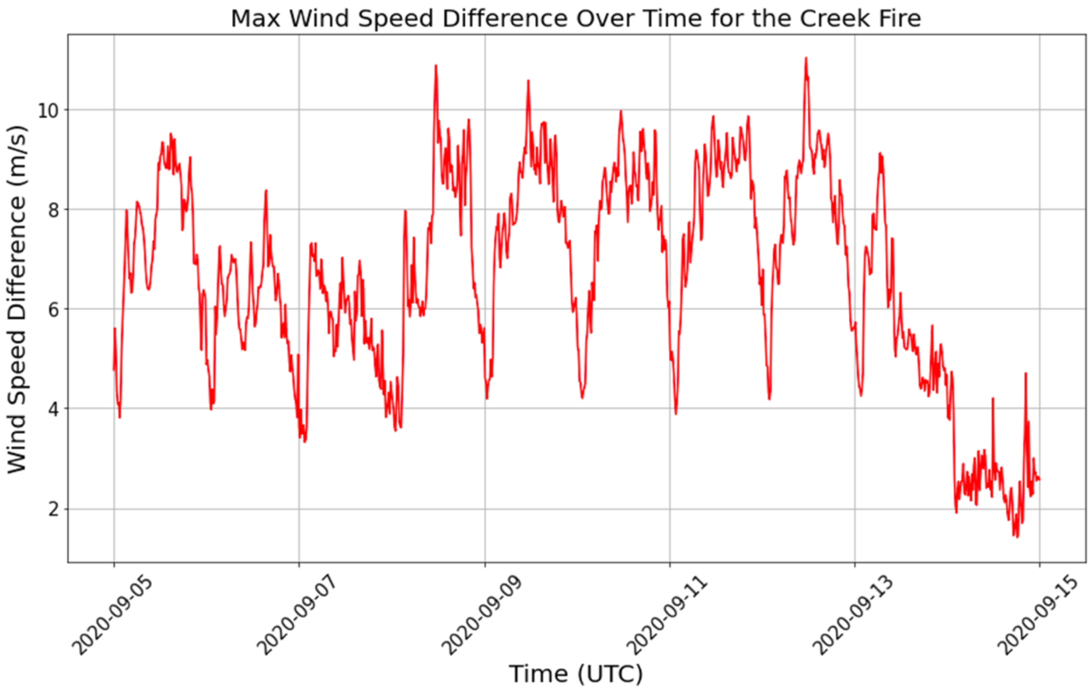
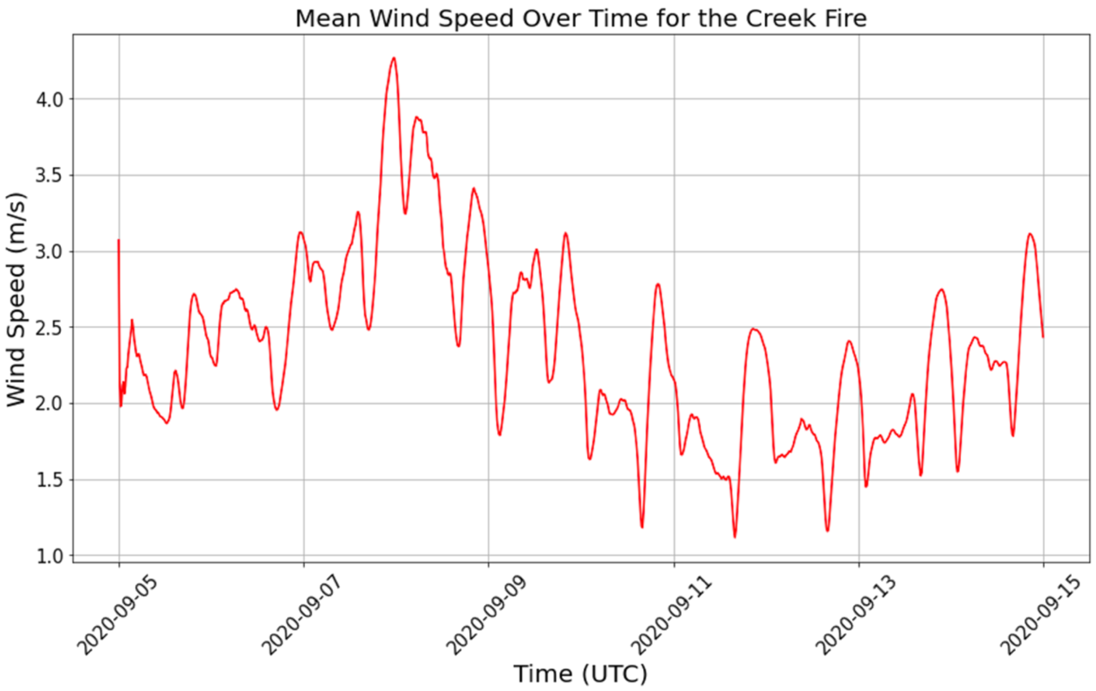
- The fire-induced winds are as fast as 11 m/s (22 mph)
- Significant diurnal trend with fire-induced winds peaking at evening/night
- The strength of the fire winds increases during the initial fire growth and decreases as the fire becomes less active

a).




b).



# Plume-Dominated Fire (Creek Fire)

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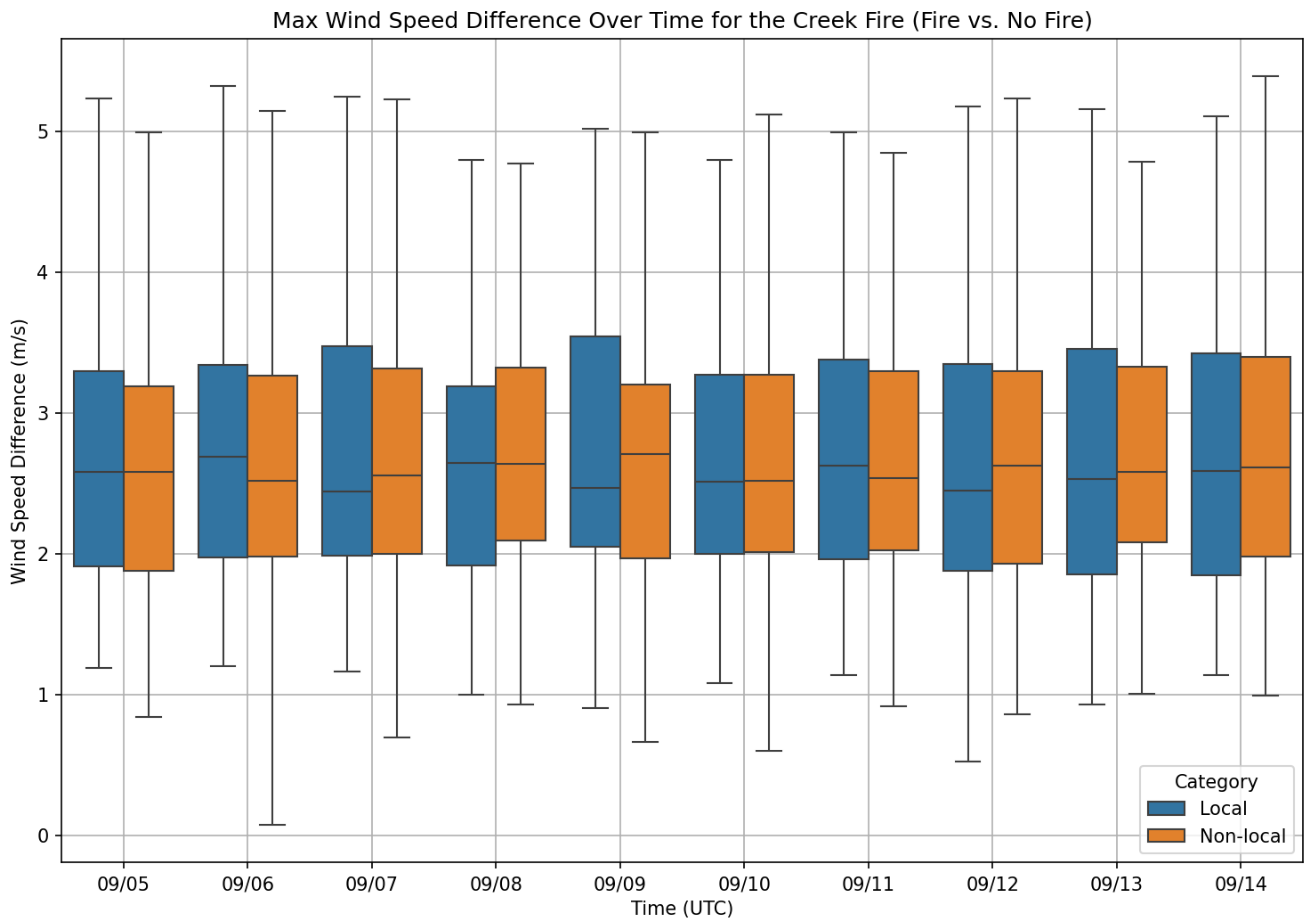
To investigate the local and non-local fire effects we computed the fire-induced wind perturbation within 5km from the fire (Local) and away from this region (Non-local)

- During the plume-dominated fire, the fire effects have more local character
- The local fire-induced wind speed differences exceed the non-local ones



# Fire winds at larger scales

- Plume-dominated Creek Fire
  - Fire winds stronger than ambient winds, reaching 25 mph
  - Diurnal cycle
  - Mostly local effects near the fire front

# Wind isn’t everything

- Analysis of the precipitation induced by the fire

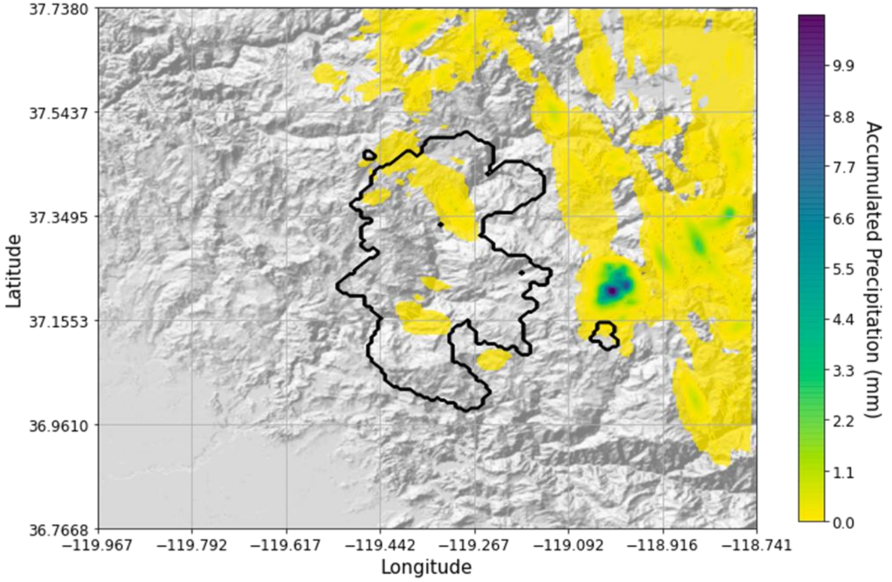
# Plume-Dominated Fire (Creek Fire)

Cloud activity was observed during the Creek Fire.

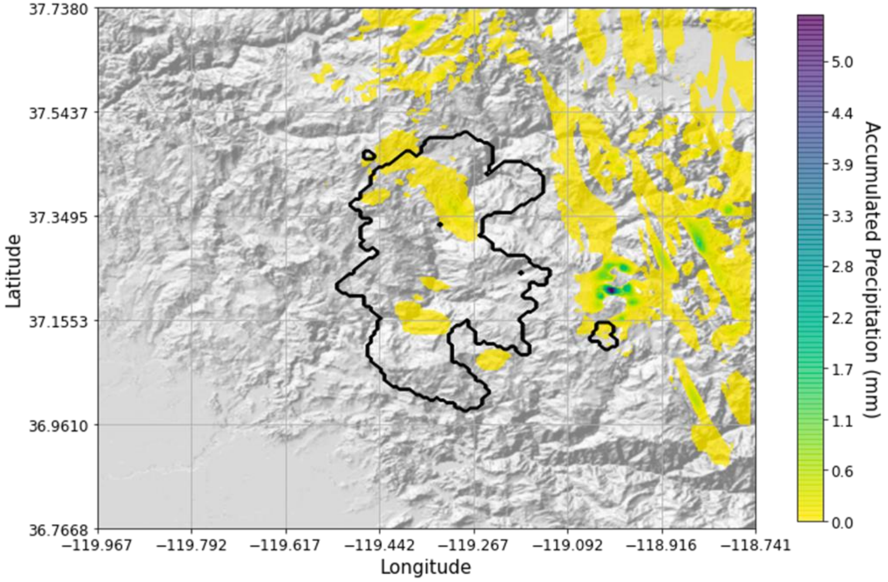
In order to assess the impact of the fire on precipitation we computed the fire-induced precipitation as a difference between the coupled and uncoupled simulation

The fire was responsible for generating up to 5 mm of rain, which is up to 50 % of the total.

a). Total Precipitation



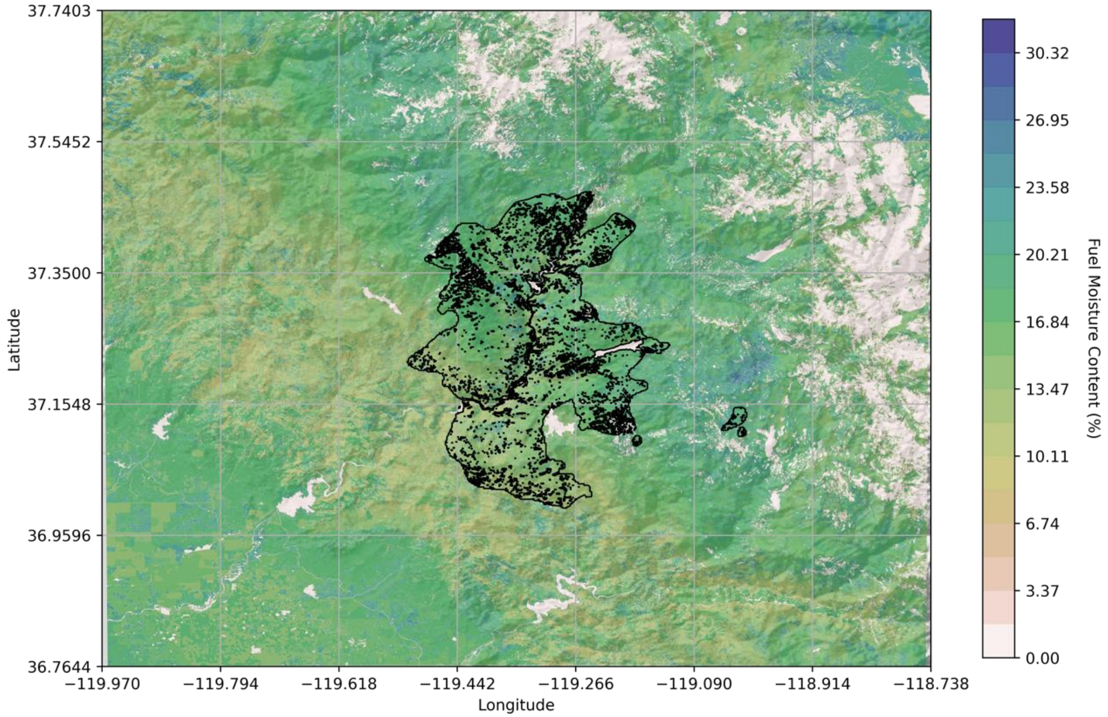

b).Fire-induced precipitation




Precipitation augmented mostly on the eastern side of the fire

# Plume-Dominated Fire (Creek Fire)

- The precipitation increased fuel moisture over the eastern part of the domain
- The additional precipitation **reduced the fire rate of spread by up to 13%.**

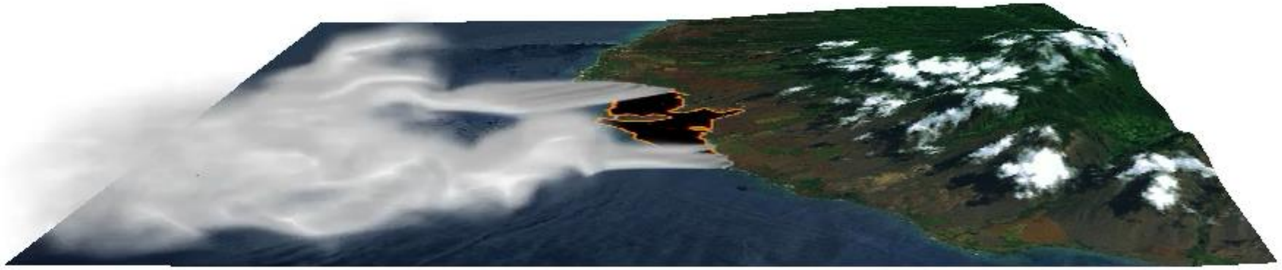



| Date: 11 September 2020 | | Date: 12 September 2020 | |
|---|---|---|---|
| Fire ROS | 0.1725 m s-1 | Fire ROS | 0.2476 m s-1 |
| No Fire ROS | 0.195 m s-1 | No Fire ROS | 0.2661 m s-1 |
| Percent Difference | 13.04% | Percent Difference | 7.47% |

# Can a Fire Slow Itself Down by Altering Local Weather, Even Without Rain?

- Analysis of the interaction between the fire and the hydraulic jump during the Lahaina fire

# Dynamical Effects During Lahaina Fire



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Lahaina Fire broke out on August 8, 2023 , as a part of the devastating Maui wildfires that occurred in Hawaii during a downslope wind storm.

Here are key details about the Lahaina Fire:

- **Area burned**: The fire scorched approximately **2,170 acres** on the island of Maui, primarily in the historic town of Lahaina.
- **Damage**: The fire almost completely destroyed Lahaina, a historic town and a former capital of the Hawaiian Kingdom, leveling over **2,200 structures**, including homes, businesses, and cultural landmarks.
- **Fatalities**: Tragically, the Lahaina Fire resulted in at least **97 confirmed deaths**, making it the **deadliest wildfire in the U.S. in over a century**.

# Dynamical Effects During Lahaina Fire

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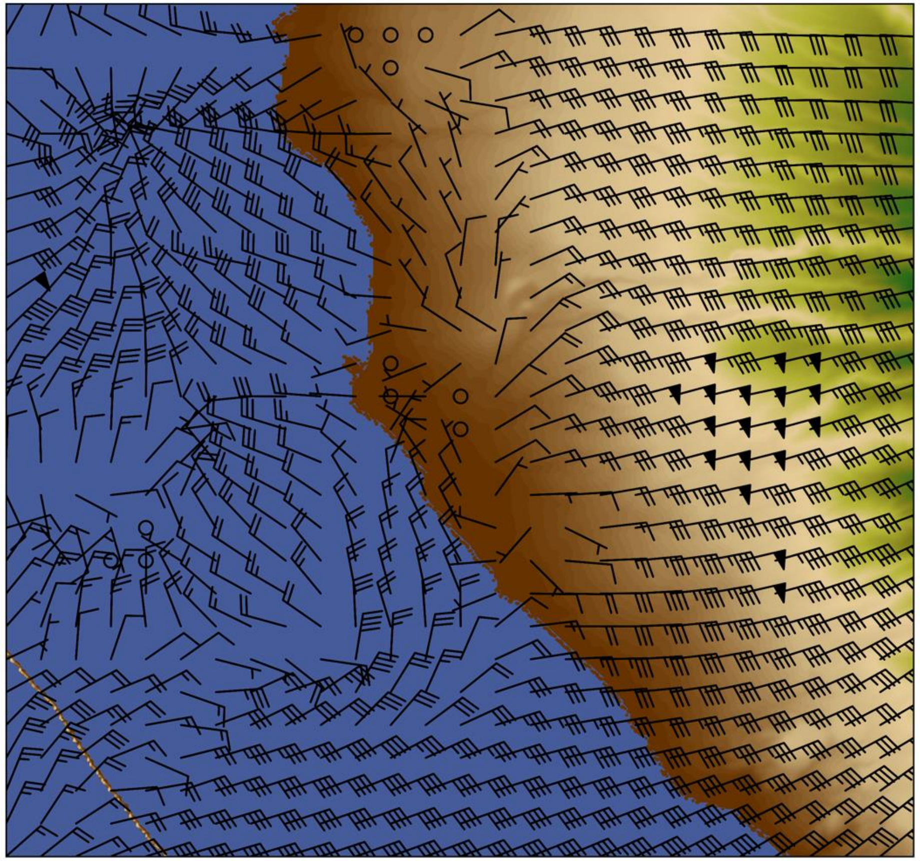
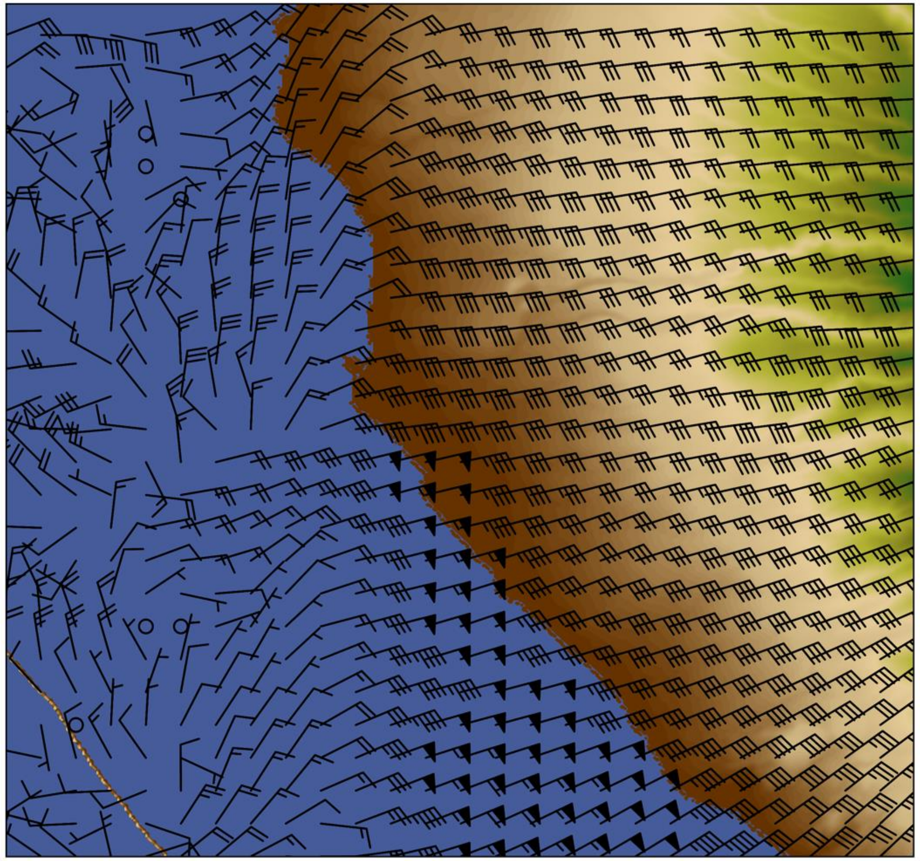
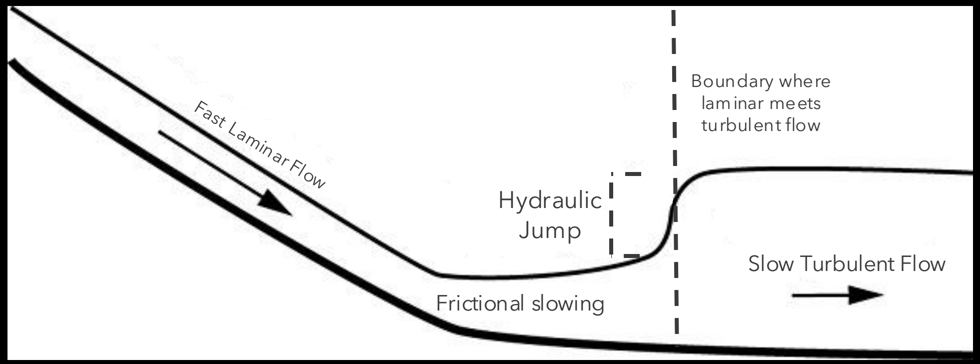
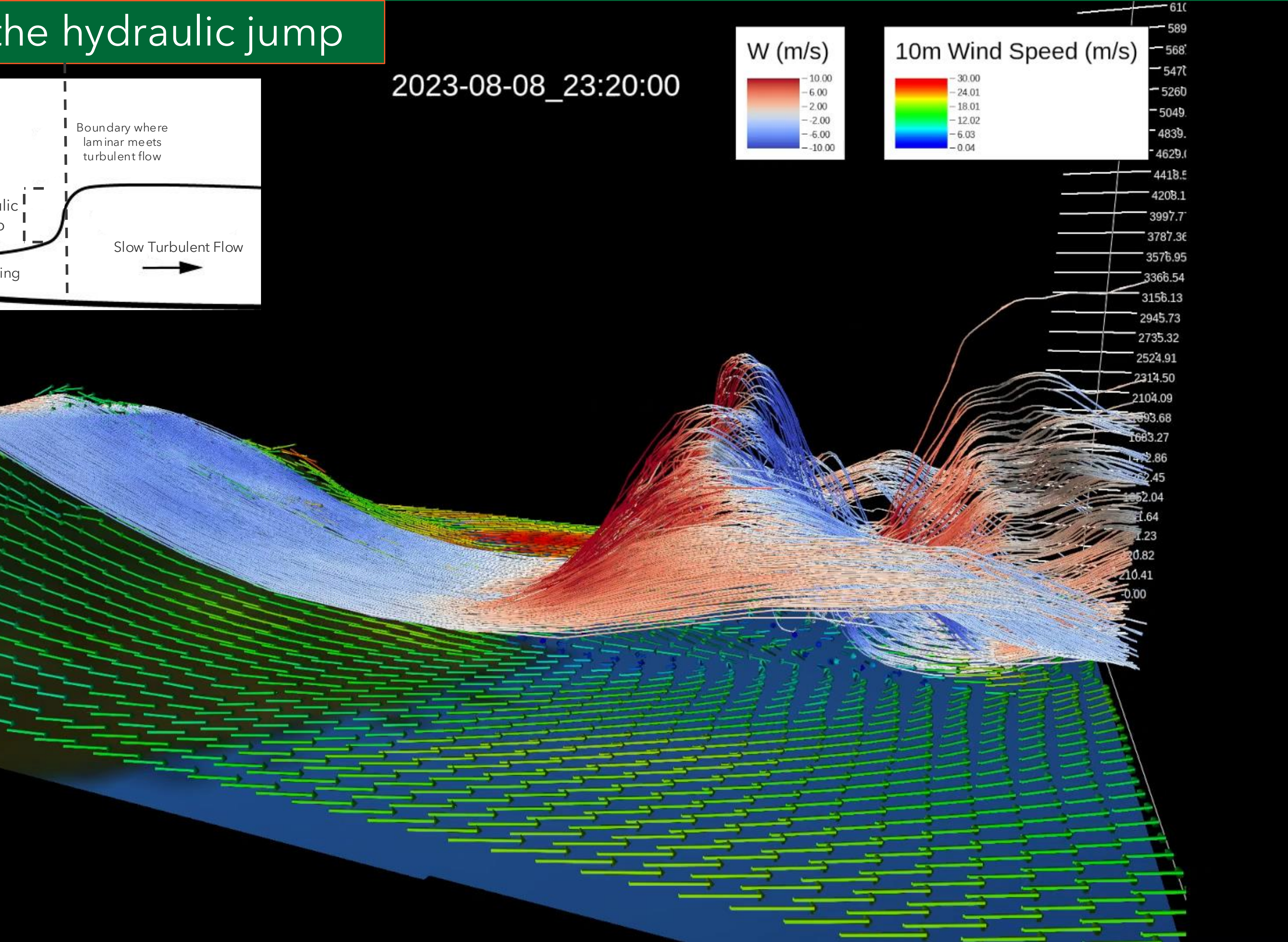
- The region of strong winds propagating slowly toward the shore
- Very turbulent winds formed ahead of the wind front
- Offshore movement of the front brought very strong winds that fueled the initial fire propagation

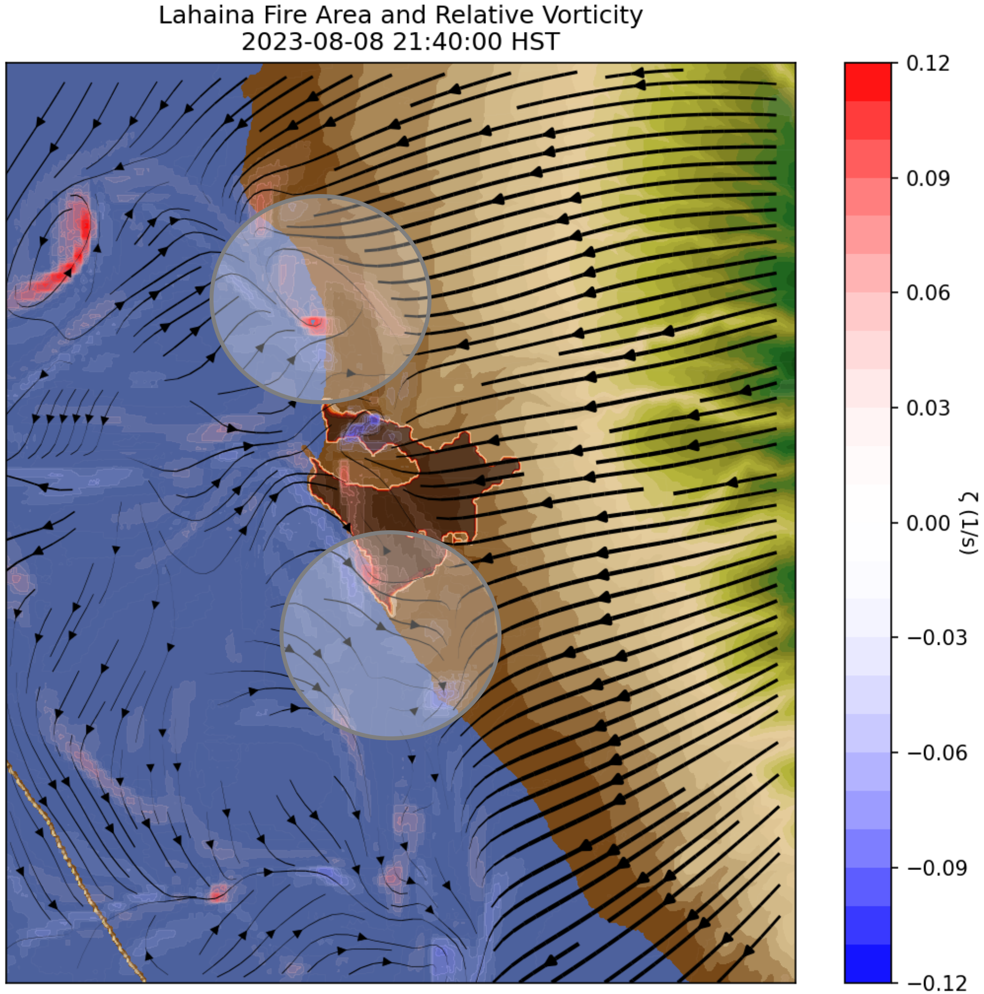


# 3D Visualization of the hydraulic jump




Lahaina Fire Area and Relative Vorticity
2023-08-08 21:40:00 HST
0.12
0.09
0.06
0.03
0.00
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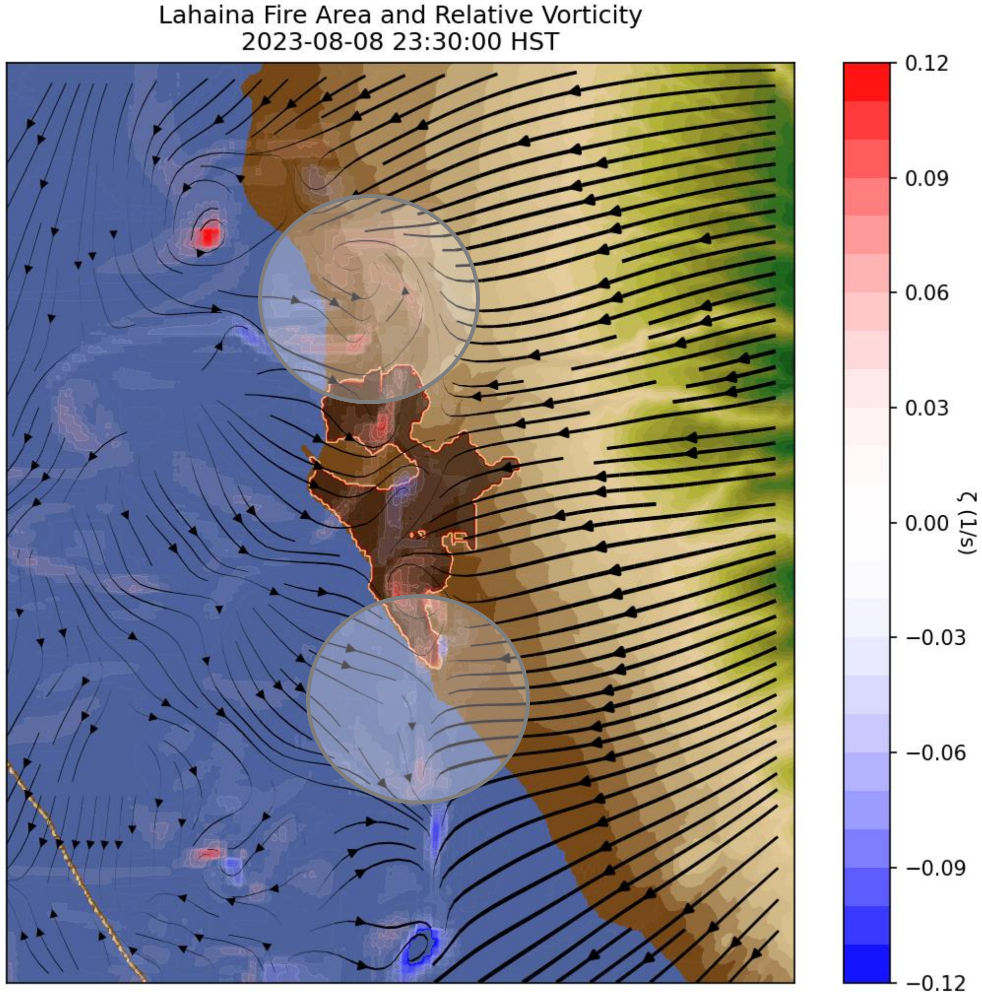
−0.09
−0.12
ζ (1/s)


Lahaina Fire Area and Relative Vorticity
2023-08-08 23:30:00 HST
0.12
0.09
0.06
0.03
0.00
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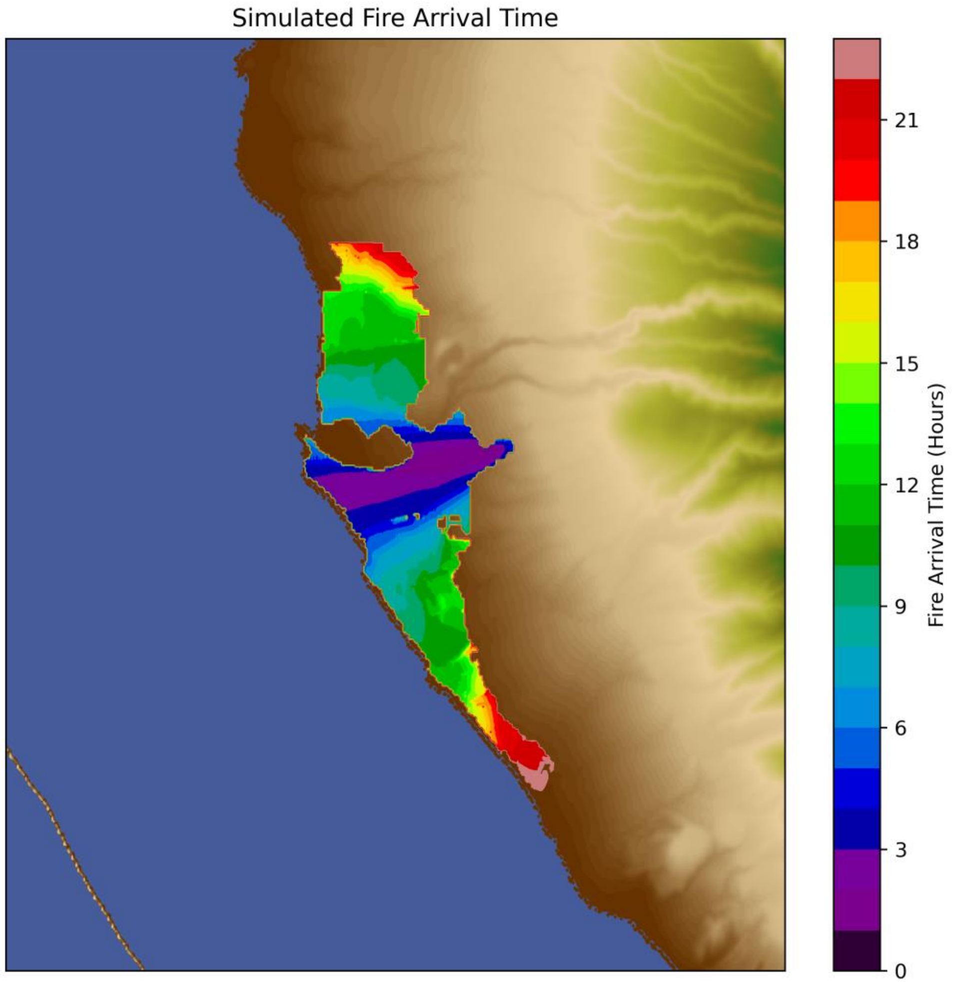
−0.09
−0.12
ζ (1/s)

# Dynamical Effects During Lahaina Fire

- The fire fueled by the strong offshore winds (up to 80 mph) reaches the coast in just a few hours
- Then, the lateral fire growth starts at the northern and southern flank
- The turbulence associated with the hydraulic jump drives the lateral fire growth



# Dynamical Effects During Lahaina Fire

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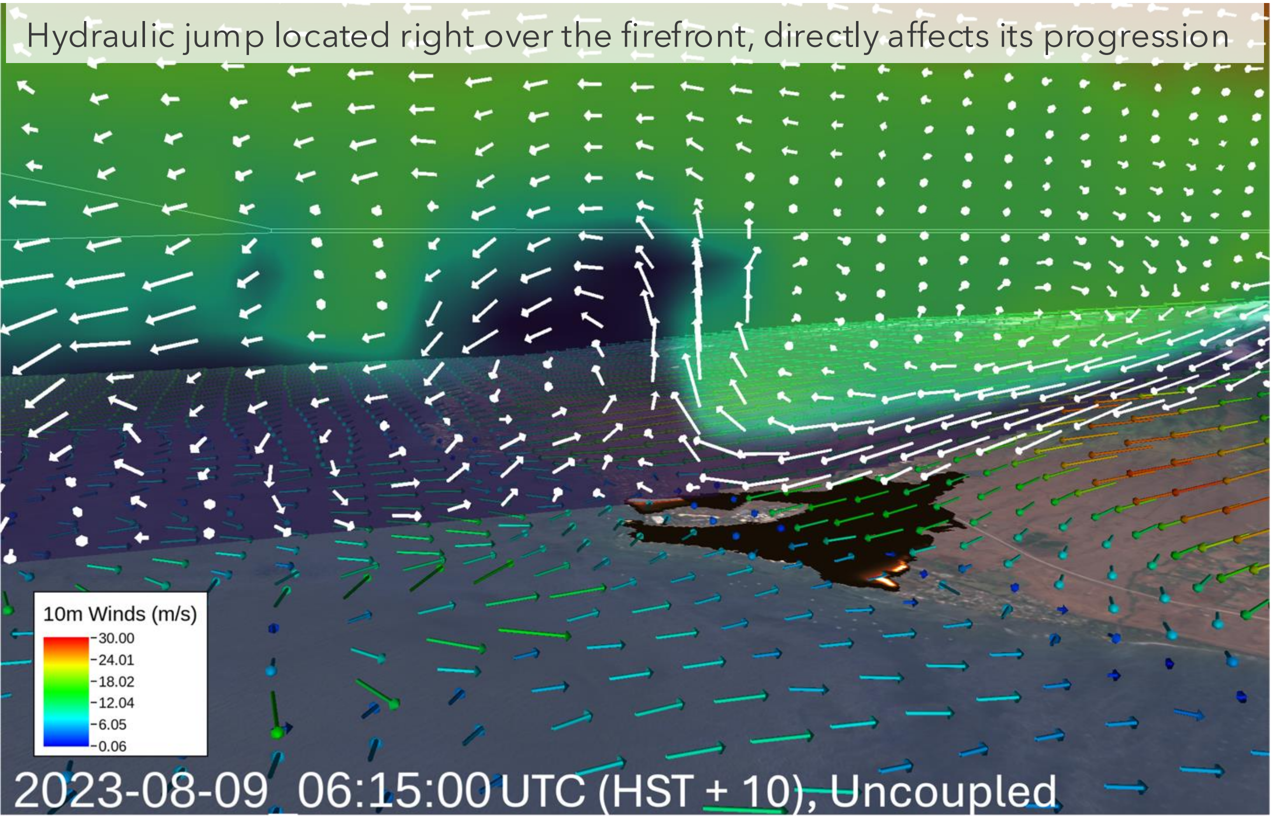
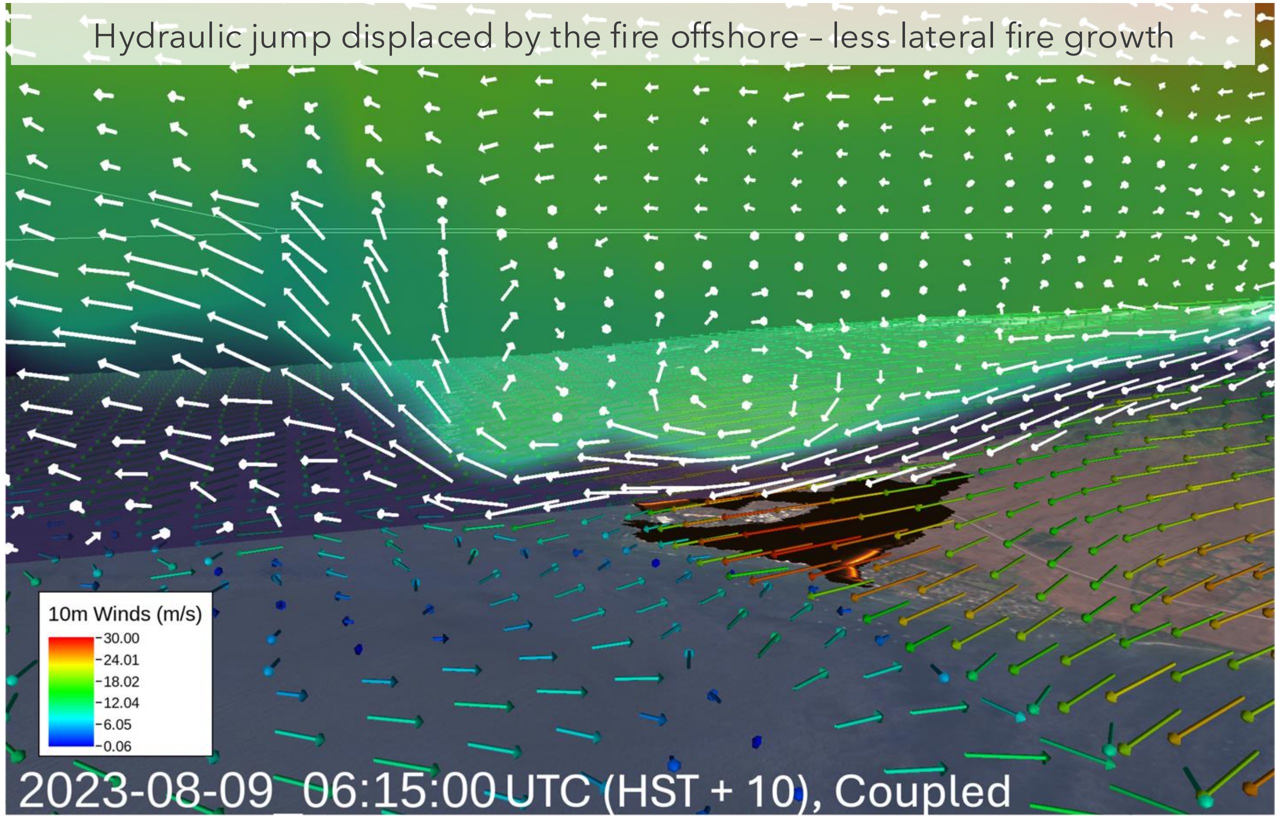
- The fire was strong enough to displace the hydraulic jump
- The offshore movement of the hydraulic jump reduced the influence of the vortices on the fire propagation and reduced the lateral progression of the fire in the uncoupled simulation

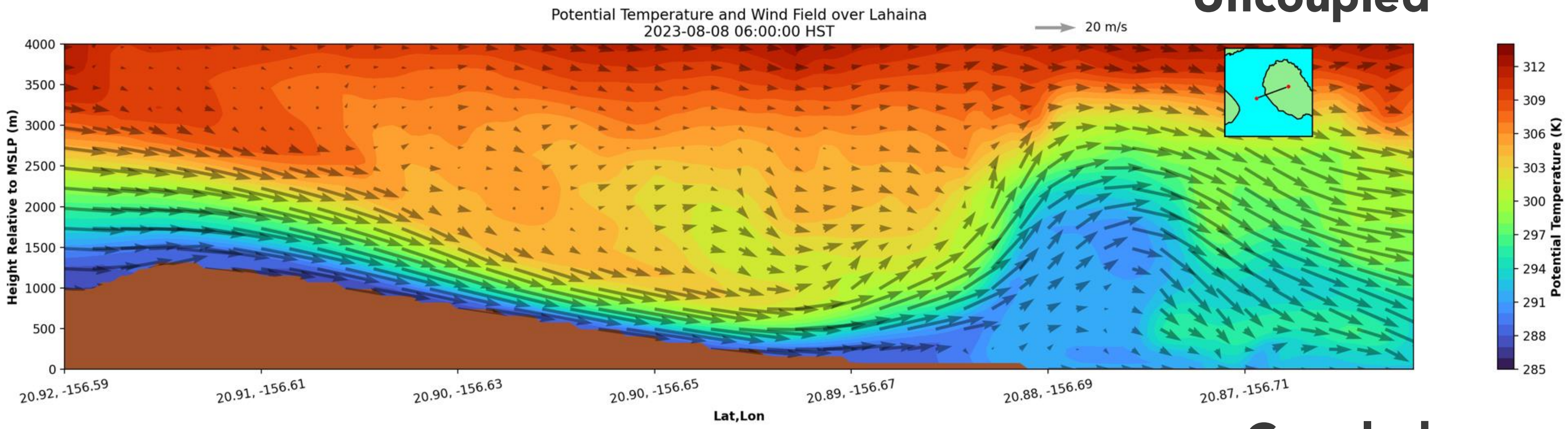


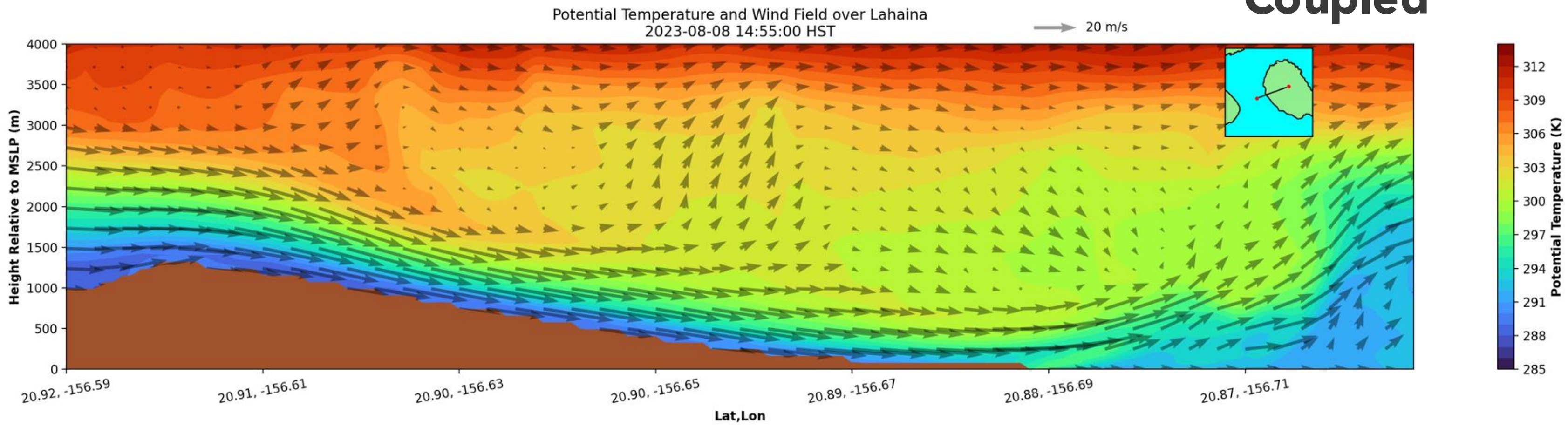
# Dynamical Effects During Lahaina Fire

- The fire enhances surface winds which push the hydraulic jump offshore
- Since the fire progression is limited by the coastline, after the initial stage, the most critical factor in the fire progression becomes the strength of the cross-winds that could support lateral fire spread
- The displacement of the hydraulic jump leads to less turbulent flow near the flanks and results in slower lateral fire growth in the coupled simulation

**Uncoupled**

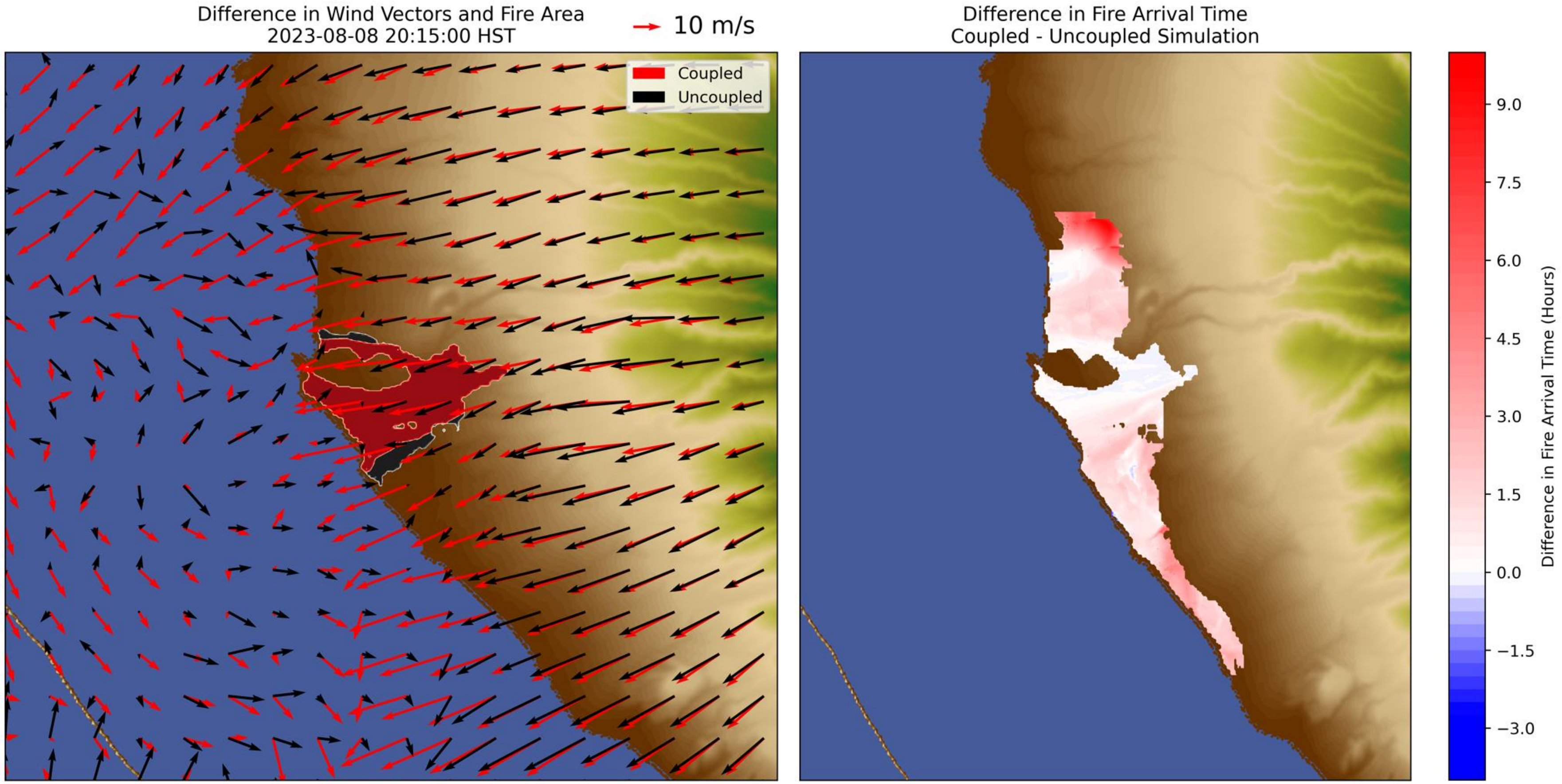



**Coupled**



# Dynamical Effects During Lahaina Fire

- The fire-induced circulation makes winds more uniform and reduces the impact of vortices associated with the hydraulic jump
- As a consequence, the lateral progression of the fire in the coupled simulation is delayed compared to the uncoupled one
- In this case, the fire-induced circulation limits the fire growth



# Summary

Wildfires have a profound effect on the fire environment

The mechanisms of fire-induced atmospheric perturbations may vary

In idealized cases, the inflow into the base of the convective column enhances winds

In plume and wind-driven fires, the character of fire-induced winds differ

Plume-dominated fires can enhance precipitation, increase fuel moisture, and reduce fire spread

The dynamic effects of fire-atmosphere coupling may be very complex and either enhance or limit fire activity

Coupled fire-atmosphere models can capture fundamental effects of fire-atmosphere interactions

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# Thank You

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https://www.wildfirecenter.org/wildfire-information

https://www.fuelmoisture.us

https://www.nfmdb.org