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Brief communication: The Lahaina Fire disaster: How models can be used to understand and predict wildfires

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Abstract. Following the destructive Lahaina Fire in Hawaii, our team has modeled the wind and fire spread processes to understand the drivers of this devastating event. The results are in good agreement with observations recorded during the event. Extreme winds with high variability, a fire ignition close to the community, and construction characteristics led to continued fire spread in multiple directions. Our results suggest that available modeling capabilities can provide vital information to guide decision-making and emergency response management during wildfire events.

1 Introduction

The wildland urban interface (WUI) fire that destroyed the town of Lahaina, HI on 8-9 August 2023 ranks as the deadliest fire in the past 100 years in the USA. More than 100 lives were lost with 385 people missing a month after the event, and about 2200 structures were damaged or destroyed with an estimated rebuilding cost of $5.5 billion (University of Hawai'i News, 2023). The large-scale weather conditions during the event were characterized by a high-pressure region northeast of Maui and Hurricane Dora to the south, creating strong east-to-west winds impinging on Maui, and thus, a favorable environment for a downslope windstorm along the Island's lee (west-facing) slopes. The goal of this brief communication is to provide physical insight into the meteorological drivers and fire spread processes leading to this tragedy. Specifically, we show that:

(1) A severe downslope windstorm with more than 30 m/s sustained winds drove the initial east-to-west fire spread into and through Lahaina.
(2) Subsequent fire spread to the north, south, and east was driven by the inland migration of a hydraulic jump and associated turbulent flow, causing highly variable fire spread through the built environment.
(3) A combination of fire spotting due to high winds, construction types, and building density in the region led to fast fire spread inside the community.

Combined, the fire's initial rapid westerly spread and subsequent lateral spread conspired to make it challenging to predict the fire behavior and make decisions related to evacuation and response.

2 Methods

(1) We use the Weather Research and Forecasting (WRF) model (Skamarock et al., 2019) initialized from High-Resolution Rapid Refresh (HRRR, Dowell et al. 2022) analysis fields to simulate the downslope wind storm. The model is configured using two domains, with the outer and inner domains resolved at 900 and 100 m horizontal grid cell spacing and covering regions of 162 and 36 km^2, respectively. The inner domain, centered on west Maui, is run in large-eddy simulation (LES) mode, allowing it to explicitly resolve the dominant scales of turbulence.

(2) We subsequently use the wind fields extracted from WRF at 15-minute intervals to drive the Streamlined Wildland-Urban Interface Fire Tracing (SWUIFT) model for urban fire spread (Masoudvaziri et al., 2021). SWUIFT operates with a 5-minute temporal resolution and a 10 m grid spacing. An area of about 9.3 hectares, east of Lahainaluna Rd and the Lahaina Bypass, is ignited inside vegetation to initiate the simulation. This area is close to the location where a flareup of the Lahaina Fire was reported to have occurred before 3:30 PM (County of Maui, 2023).

WRF and SWUIFT are, respectively, well-validated models for simulating downslope windstorm-driven fires and WUI fire spread. The models' capabilities have been recently demonstrated simulating the Marshall Fire (Juliano et al., 2023), the Tubbs Fire (Masoudvaziri et al., 2023), and the Camp Fire (Shamsaei et al., 2023; Szasdi-Bardales et al., 2023), to name a few. The fire spread simulation does not consider the effects of structure hardening and suppression.

3 Results

3.1 Meteorological Drivers

Figure 1 shows the flow fields before and during the fire's active burning to highlight the evolution of the atmospheric vertical structure and near-surface winds. These data show:

(1) On the morning of the fire (5:00-5:45 AM), strong winds (>30 m/s) flow down the western slope of Pu‘u Kukui toward Lahaina (black line, Fig. 1), but detach from the surface before reaching the town in a "hydraulic" jump (red line, Fig. 1a,b). Drivers for these downslope winds and the hydraulic jump are the well-understood interaction of an approaching stable flow to a topographic barrier along with a self-induced critical layer (e.g., Durran and Klemp, 1987). The critical layer traps energy near the surface. It is self-induced in that the upstream wind profile does not have a flow reversal with height, and the observed flow reversal (i.e., positive zonal winds above the plunging flow) is thus inferred to result from wave breaking processes. Approximately two-thirds of the way down the slope, WRF also simulates regions of low-level reversed flow (red contours), coincident with the initial development of a hydraulic jump. Near the jump region,

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the mean kinetic energy contained in the fast-moving flow is converted into turbulence kinetic energy (e.g., Ball, 1956), leading to a highly variable low-level flow field.

(2) By 9:00-9:45 AM, the edge of the downslope winds (red line, Fig. 1c,d) move closer to the town of Lahaina, and by mid-afternoon (3:00-3:45 PM), during the initial fire spread phase, the strong downslope flow extends to just offshore from Lahaina (red line Fig. 1e,f). The resulting downslope windstorm places the strongest winds just east of downtown Lahaina, near the location of the presumed ignition (County of Maui, 2023). The attached flow field means that coherent near-surface winds of ~35 m/s affect the entire town, likely accounting for the video and photographic documentation of downed trees and powerlines along with structure damage prior to the fire's arrival. This attached flow is the driver for the initial northeast-southwest fire spread through downtown Lahaina and eventual arrival at the coast.

During the nighttime hours (10:00-10:45 PM), the location of the hydraulic jump moves inland (i.e., eastward), retreating partially up the slope of Pu'u Kukui (red line Fig. 1g,h). This placed Lahaina in the turbulent rotor region beneath the jump, with mean winds reversing, now flowing from the west-to-east in contrast with the earlier period of strong east-to-west flow during the ignition. The mean-flow reversal and extreme variability of the wind are, as we show in the next section, drivers for the fire spread during the second half of the fire.

3.2 Fire Spread

Figure 2 shows the results of SWUIFT's simulation driven by the WRF wind field. By 4:30 PM (i.e., 1-hr after ignition) on August 8, 2023, the fire reaches the oceanfront, burning structures in Front Street between Baker Street and Papalaua Street. At 5:30 PM and 6:30 PM, the fire front widens with still a predominantly east-to-west progression. By 7:30 PM, the effects of the hydraulic jump's migration and turbulent flows are noticeable, with an accelerated fire spread toward the north, south, and east. The results at 8:30 PM show the fire reaching structures in the southern portion of Lahaina, while also continuing with its northward expansion.

The simulation results are in good agreement with observations from witness reports and recorded videos. For example, records indicate that people close to Front Street and Papalaua Street jump into the ocean between 4-6 PM, a video shows the town's historic Front Street on fire at 5:19 PM, Northern Lahaina begins to burn at around 7:30 PM, etc. Overall, wind-driven fire spotting causes the fire to jump across the community and radiation leads to fire spread between closely spaced structures. Lack of structure hardening in parts of the community, especially inside the historic town, increases vulnerability and the likelihood of ignition.

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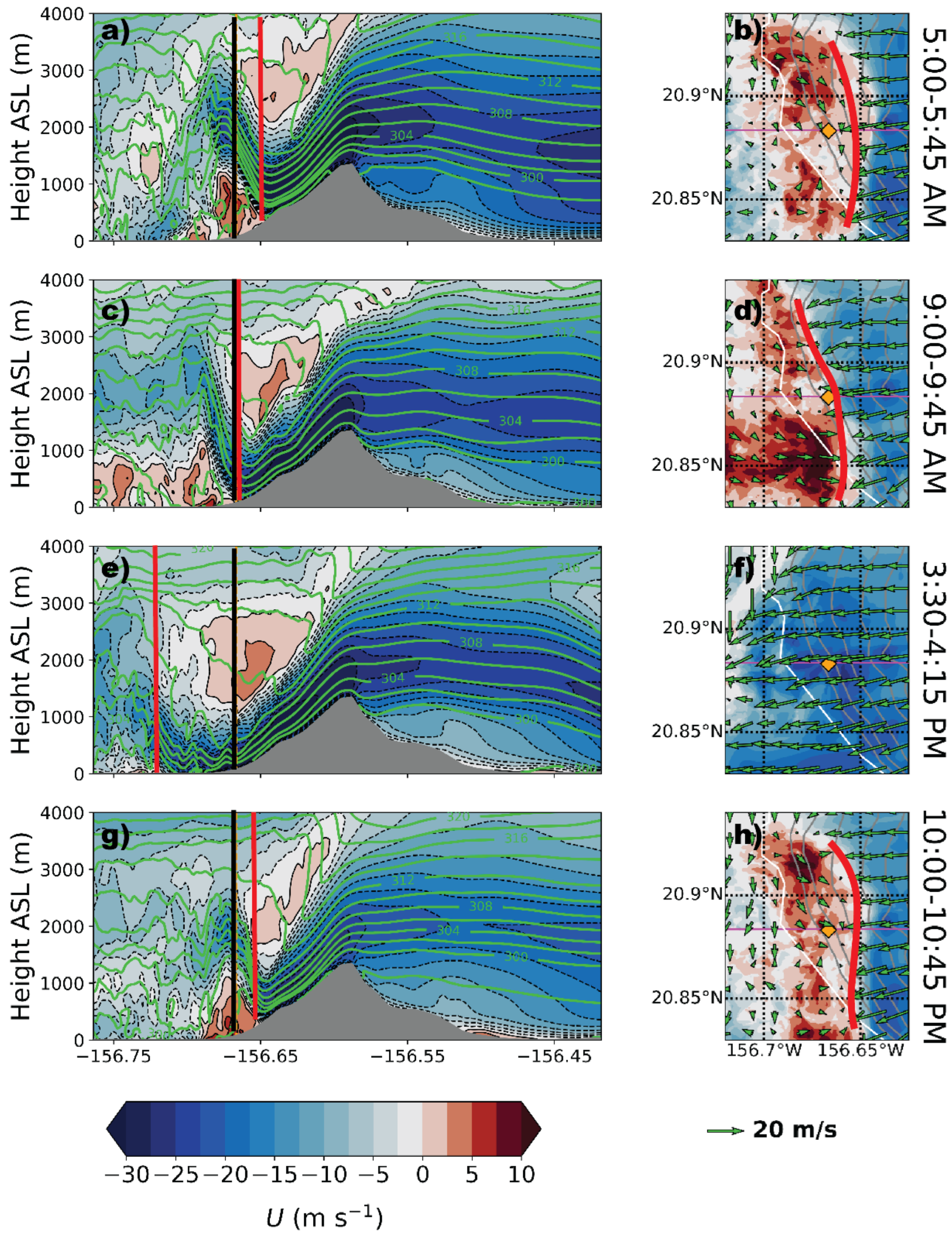

Figure 1: WRF-LES results showing the *U*-wind component at various times during the event. (a,c,e, and g) Vertical cross-sections slicing east-west through Lahaina (along ~20.88 N). Color-filled contours show the *U*-wind according to the colorbar, and green contours show the potential temperature. The terrain is color filled in gray, and the approximate location of the fire ignition (-156.667 W) is shown by the black line. (b,d,f, and h) X-Y plan views of the *U*-wind (color-filled according to the same colorbar) and wind vectors (speed according to the key) at 10 m ASL. The white line marks the coastline, while the gray contours show the

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elevation at 50, 100, 200, 400, and 600 m ASL. The approximate location of the fire ignition (20.883 N, -156.667 W) is shown by the orange diamond, and the magenta line shows the cross-section location. The approximate location of the hydraulic jump and flow reversal in all panels is shown with a red line.

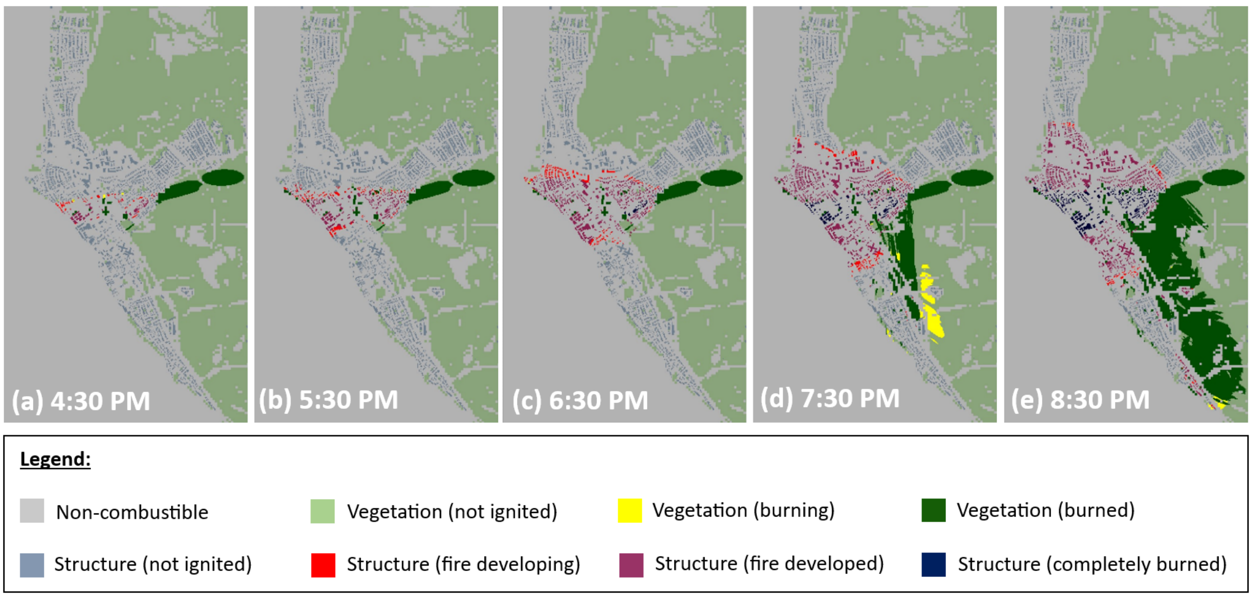

Figure 2: (a-e) SWUIFT simulation results at regular time intervals showing fire spread inside Lahaina, HI on August 8, 2023. The colors indicate non-combustible areas (e.g., roadways), the status of vegetation (not ignited, burning, burned), and structures (not ignited, fire developing, fire developed, completely burned).

4 Discussions

The meteorological drivers and fire spread processes are one factor in making this fire so deadly and destructive. The extreme winds (>35 m/s) made escape from the initial fire run challenging, especially considering the numerous downed trees and power lines. The subsequent, and rather abrupt, shift in the winds to on shore (westerly) and extreme variability was particularly insidious in that it allowed continued fire spread in all directions, and thus, those fleeing the initial east-to-west run did not have a safe haven apart from the ocean. In other words, it was not a simple situation of moving out of the path of the fire. While previous studies have highlighted the role of downslope windstorms in driving fire into the built environment (e.g., Nauslar et al., 2018; Mass et al., 2019; Abatzaglou et al., 2023), the somewhat unique aspect of this case is the subsequent role of the hydraulic jump and turbulent flow in impacting the fire spread after the initial run. The fire spread resulting from a highly turbulent region under the hydraulic jump is irregular and, therefore, harder to plan for. Similar processes appear to have been at play during the Marshall fire, wherein the location of the hydraulic jump may have impacted the fire spread characteristics (Juliano et al., 2023). Another similarity with the Marshall fire is the close proximity of the ignition to the town, leaving little warning time before the fire spread into the community, which contrasts with other

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cases where the fire burns inside the wildland for an appreciable time before reaching a WUI area (e.g., Tubbs and Camp Fires in California).

There are many additional aspects of this tragedy that require investigation, including the role of building construction types, evacuation planning and orders, blocked egress, and, sadly, the impact of marginalized population demographics on the ability to flee to safety. As has occurred in other high-impact fires, many of the fire's victims were elderly.

Although further systematic studies are essential to improve simulation accuracy and validate with the actual fire behavior, the results presented herein demonstrate our ability to characterize reasonably well the disaster that transpired on the evening of August 8, 2023, in Lahaina. Furthermore, the models used in this study can produce such predictions fast enough to be useful for decision-making. Timely dissemination of this information to the authorities could have potentially facilitated informed decision-making and bolstered emergency response management, potentially preserving human lives. This underscores the critical technology deficit that currently exists in wildfire management, which places fire response in a reactive position, regularly lagging behind the fight due to a lack of situational awareness and predictive capabilities. Development of a unified active-fire decision support system, capable of collecting, integrating, and infusing data sources, as well as providing faster-than-real-time physics-informed predictive capabilities, can revolutionize the landscape of fire response and empower our future of coexisting with wildfires.

Author Contribution

Neil P. Lareau, Timothy W. Juliano, Branko Kosovic, Negar Elhami-Khorasani, and Hamed Ebrahimian contributed to the conceptualization. Timothy W. Juliano, Fernando Szasdi-Bardales, Eric P. James, and Kasra Shamsaei conducted data curation and formal analysis. Neil P. Lareau, Timothy W. Juliano, Fernando Szasdi-Bardales, and Negar Elhami-Khorasani prepared the visualizations. Neil P. Lareau, Timothy W. Juliano, Branko Kosovic, Fernando Szasdi-Bardales, Negar Elhami-Khorasani, and Hamed Ebrahimian wrote the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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