MS No.: NHESS-2023-164
MS Title: Brief communication: The Lahaina Fire disaster: How models can be used to understand and predict wildfires

Reviewer 1

General comments

This paper presents simulations of the wind and fire spread during the Lahaina fire in August 2023. Since the simulations match the observed behaviour of the fire, the authors illustrate the potential value of these types of models for emergency response. The paper is well suited for a brief communication in NHESS as it reports on a topical event of scientific and social interest. The study was well designed and the paper is well written, so I only have minor comments and suggestions for consideration.

The authors sincerely thank the Reviewer for the time and effort in reviewing our manuscript. Each of the comments and suggestions made by the Reviewer is addressed in the following note. Added text is shown in bold and underlined format.

Specific comments

1. The wind and fire model results are presented with different timestamps which make it difficult to clearly link the fire behaviour with the movement of the hydraulic jump. I think improving the use of timestamps could make several things clearer (see technical comments).

Author Response:

We address this below, but as an overview, we feel it is appropriate to present these data at different time scales because the flow and fire evolve at different time scales. We have added additional figure panels for the period from 6:45-7:30 PM (Fig. 1g,h) to aid in the interpretation and included further descriptive text to explain this in the manuscript.

2. The title poses the question of "how models can be used to understand and predict wildfires", but from my impression the results primarily demonstrate "understanding" with less discussion about the "prediction". There are some brief comments in the Discussion about how these models are fast enough for decision making (line 121) and the development of a unified system being revolutionary (line 126), but based on the title I was expecting a bit more detail about what would be needed to implement these methods for real-time decision making. I encourage the authors to elaborate on this point.

Author Response:

Thank you, we have added text to address this comment, please see response to the last comment for details.

Technical comments

1. Methods: It was not immediately clear when first reading that all the timestamps are on Aug 8, since the introduction says the fire was on Aug 8-9. This could be clarified by explicating stating in the methods something like "the simulations covered Aug 8 when the fire initiated and spread". Then in subsequent parts of the paper, simply citing a time of day would suffice.

Author Response:

We have added a sentence in the Methodology section to address the above comment: **"<u>The wind and fire spread simulations focus on the events of August 8th, 2023, when the fire initiated and spread in Lahaina</u>."**

2. Line 43: While I'm not a wildfire modeller, I would have assumed there are limitations to simply forcing a fire spread model with wind from at weather model compared to a coupled model that actually captures the impact of the fire on the wind field. Based on these citations, and the results of this study, I suppose this may not be the case?

Author Response:
It is known that large wildfires generate their own updrafts and intense local winds, which can drive the fire spread. Thus, coupled weather-fire spread models provide more accurate fire spread simulations in the wildland. The Lahaina Fire was mainly a WUI fire with structures serving as fuel. To the best of our knowledge, there is no coupled weather-fire spread model for WUI and urban fires. In this case, a coupled model will most likely not impact the "down-slope windstorm" much, considering the strength of the mesoscale forcing. We hypothesize that coupled effects would remain very localized in wind-driven fire events. Previous applications of SWUIFT to simulate fire spread inside WUI communities (e.g., Fountaingrove in the 2017 Tubbs Fire, Paradise in the 2018 Camp Fire, Louisville and Superior in the 2021 Marshall Fire), for which weather and fire models were not coupled, provided good results considering the uncertainties during a fire event. It should be noted that a similar "down-slope windstorm" patterns affected the Camp Fire and the Marshall Fire. In general, it can be expected that the results will be further improved if the coupling effect is added, and this is something that the team hopes to implement as expanding the research.

3. Fig 1: Why are the WRF-LES results shown for spans of time rather than a single timestamp (e.g., 5:00 – 5:45 AM)? Do the plots show the averaged values over these periods to give smoother results, or would it be simpler to show single timestamps instead? Also, the axis label on 1f says 3:30-4:15 PM whereas line 62 says 3:00-3:45. The length of time windows should be consistent. The 5 AM and 9 AM plots seem similar, is it necessary to show two timestamps before the fire?

Author Response:
Because the flow is turbulent and our simulation is a single realization of the event (rather than, say, an ensemble), using time-averages rather than single snapshots better captures the important flow features (e.g., the mean location of the hydraulic jump). We were concerned that if we presented single snapshots, then a reviewer might question how representative that snapshot was of the conditions over a broader period of time.

We added text making this clearer to the reader:
"**Because the flow is turbulent and our simulation is a single realization of the event (rather than, say, an ensemble), we use time-averages rather than single snapshots to capture the important changes in the location of flow features (e.g., the mean location of the hydraulic jump) as they pertain to the evolution of fire.**"

as well as in the Figure 1 caption:
"**All fields are time-averaged according to the displayed time periods.**"

The labeling and text pertaining to time windows have been corrected. Thank you for pointing this out.

While there are qualitative similarities in the flow structure for 5 AM and 9 AM, the location of the hydraulic jump (marked by the red line) transitions from upstream of the nominal ignition location (yellow diamond) to immediately over the ignition location, thus reflecting the onset of the strong downslope winds proximal to Lahaina. This is a critical transition in the event. Thus, we'd prefer to keep both these panels as the onset time of downslope winds (and the location of the hydraulic jump) is a key forecasting challenge both in the present case and in other similar environments (e.g., Santa Ana wind onset time in southern California). We added some additional text to make it more clear why we included these two panels. This text is in bullet point 2 and reads:

“**By 9:00-9:45 AM, the leading edge of the downslope winds and the hydraulic jump (red line, Fig. 1c,d) moves westward and closer to the town of Lahaina, near the location of the presumed ignition (County of Maui, 2023). This transition marks the onset of extreme winds capable of driving extreme fire spread. By mid-afternoon (3:30-4:15 PM), during the initial fire spread phase, the leading edge of the strong downslope flow extends to just offshore from Lahaina (red line, Fig. 1e,f).**”

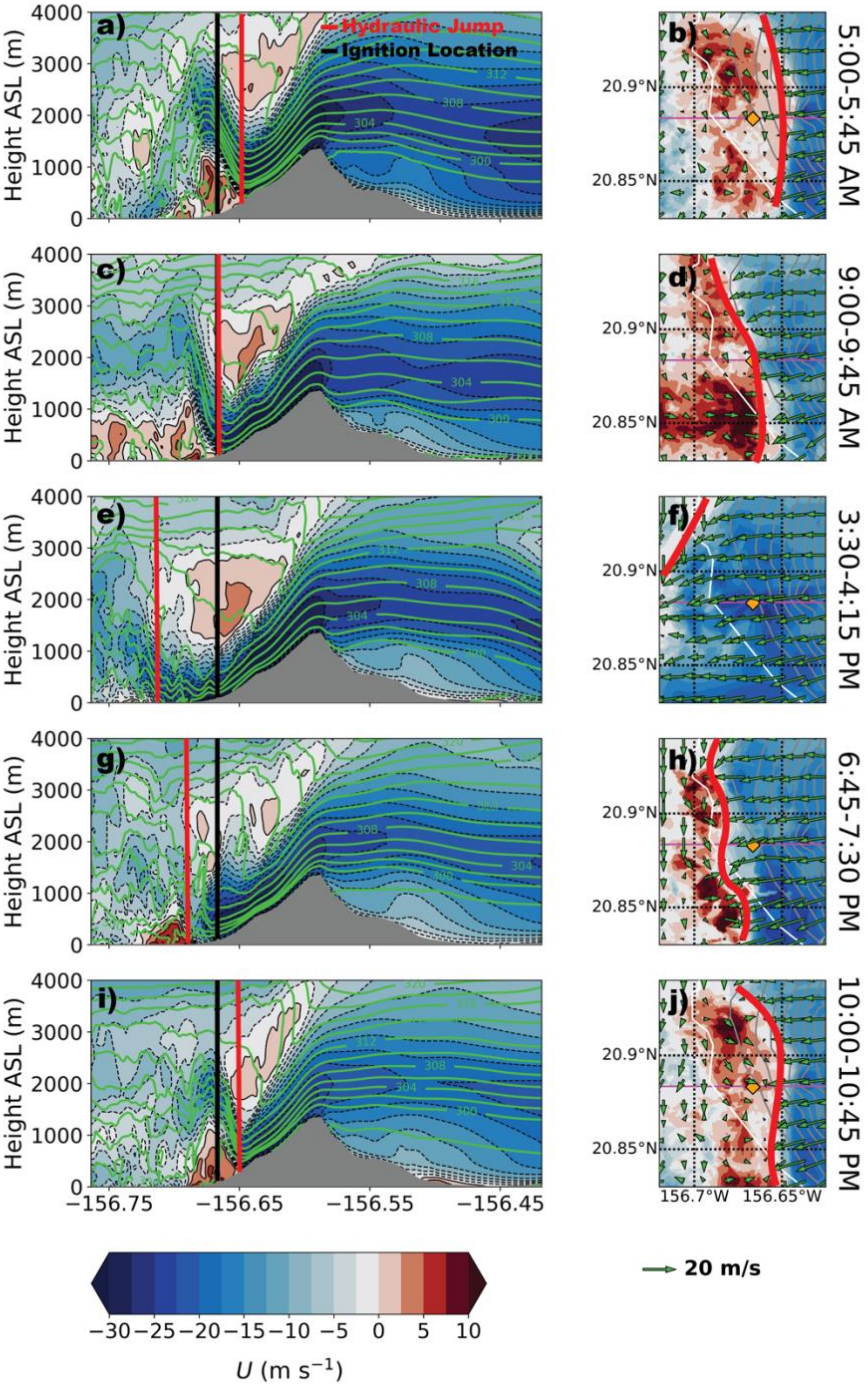

Figure 1: WRF-LES results showing the *U*-wind component at various times during the event. (a,c,e,g, and **i**) Vertical cross-sections slicing east-west through Lahaina (along ~20.88 N). Color-filled contours show the *U*-wind according to the colorbar, and green contours show the potential temperature. The terrain is color filled in gray, and the approximate location of the fire ignition (-156.667 W) is shown by the vertical black line. (b,d,f,h, and **j**) 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 **elevation at 100 m intervals**. 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. **All fields are time-averaged according to the displayed time periods.**

4. Lines 68-72: For consistent formatting, shouldn't these sentences be item number (3) in the list?

Author Response:
The Reviewer is correct. We have modified the formatting to make these sentences item number (3) in the list.

5. Line 93: It seems odd to use irregularly spaced intervals for elevation contours.

Author Response:
We have modified the figure to show regularly spaced elevation contours (every 100 m).

6. Fig 2: It's confusing how these timestamps do not align with the ones in Fig 2. Wouldn't it be clearer to show things at concurrent times to make clearer links about the wind features and the fire?

Author Response:
Since the fire and wind evolve at different time scales and some critical components of the fire spread are occurring during an initially relatively consistent wind field (e.g., Fig. 2a, b) the fire evolution (house to house) is progressing while the winds are quasi-stationary. As such, we feel it makes sense to use different time stamp conventions to best capture the large-scale changes in the flow field in Fig. 1 and the fine-scale aspects of the fire spread in Fig. 2. To try to make this more clear to the reader, we have made the following revisions:

(a) We added a new subpanel to Fig. 1 to cover more of the period of fire spread shown in Fig. 2. This appears as Fig. 1g,h, which shows the retrogression of the hydraulic jump between 6:45 PM and 7:30 PM.

(b) We modified section 3.2 to explain our rationale and to make more explicit links between the two figures:

"Fig. 2 shows the results of SWUIFT's simulation driven by the WRF wind field. **Since the fire spread evolves more rapidly than the changes in the background flow field (e.g., Fig. 1), the results of the fire spread focus on a narrow time window of 4:30-8:30 PM. The simulation of fire spread indicates that the initial fire run, from 3:30-4:30 PM, progresses in a narrow along-wind path from the ignition location to the oceanfront (Fig. 2a). The fire moves from vegetation (dark green shading) to structures (red and blue) and continues to burn the structures, including those on Front Street between Baker Street and Papalaua Street. At 5:30 PM and 6:30 PM (Fig. 2b,c), the fire front slowly widens in the across-wind direction, burning structures to the north and south of the initial along-wind run. By 7:30 PM, the effects of the hydraulic jump's retrogressive migration (e.g., Fig. 1g, h) and turbulent flows are noticeable, causing accelerated fire spread toward the north, south, and east (Fig. 2d). The change in winds during this time transformed what had been "flanking and backing fire" into "episodic head fire runs" in all directions.** The results at 8:30 PM (Fig. 2e) show that the continued retrogression of the hydraulic jump facilitated the fire reaching structures in the southern portion of Lahaina, while also continuing with its northward expansion."

7. Line 83-85: Are these processes shown by the model results or based on observed events? For example, does the model simulate fire spotting and is structure hardening a parameter in the SWUIFT model?

Authors response:
Lines 83-85 were based on the model results. The following statement is added in the Methodology section to clarify the modes of fire spread in the model:
"**The SWUIFT model captures both near-field and far-field transport mechanisms of fire spread (i.e., radiation and fire spotting) between buildings and vegetation inside a community."**

Also, lines 83-85 are edited as follows: "Overall, **based on the model results,** wind-driven fire spotting causes the fire to jump across the community and radiation leads to fire spread between closely spaced structures."

The presented results do not consider structure hardening as the information on construction details is not readily available. However, the team is working on collecting detailed building inventory and simulating the fire spread to capture the influence of construction features. The original manuscript included a statement that "the fire spread simulation does not consider the effects of structure hardening and suppression."

8. Line 121: Please elaborate on this point to support the title of the paper. Based on your experience running the simulations, what would be needed to implement this in real-time and what barriers need to be addressed? This would be a valuable addition to the paper.

Authors response:
Thank you for your comment, we have edited the text to address the above comment.

"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. **While the modeling capabilities exist in the research environment, developing an active-fire decision-support technology platform to streamline data sources and integrate data with models to yield actionable information in the near real-time is currently missing. Such a technology platform requires the capability to monitor and identify the ignition and fire perimeters in near real-time. It, moreover, needs to collect and process data identifying the weather and fire spatial domain (e.g., meso- or synoptic-scale forcing), wildland fuel characteristics, WUI domain and fuel characteristics, evacuation routes, and community and social demographics. Once the domains and inputs are defined, the next step is to simulate ensemble scenarios of fire spread in the wildland and WUI to account for uncertainties and process the outcomes into useful information that can inform decision-making for various stakeholders. The process is computationally intensive and requires cloud computing and advanced data communication capabilities.**
While the SWUIFT simulation for Lahaina took 30 minutes to run, the WRF simulation for this study took 12 hours wall-clock-time to simulate about 38.5 hours of the event, i.e., almost 3:1 real-to-simulated time ratio. It is important to note that the WRF simulation was run on 288 CPU processors on the NCAR-Wyoming Cheyenne Supercomputer. For operational purposes, it would be possible to further optimize and streamline simulations to achieve 5:1 or 6:1 real-to-simulated time ratio on currently available CPU-based platforms.

In summary, timely dissemination of ~~this~~ information **on potential extreme fire behavior** to authorities ~~could have potentially~~ **can facilitate** informed decision making, ~~and bolstered~~ **bolster** emergency response management, **and** ~~potentially preserving~~ **preserve** human lives. ~~This~~ **The Lahaina Fire and presented results** underscore 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.**"

Reviewer 2

General comments

This was a concise and useful assessment of the fine-scale weather and fire spread modeling for the August Lahaina fire. I don't see any obvious flaws in the short piece and find that the combination of WRF runs with SWUIFT models is a useful combination in understanding this -- and other -- extreme urban wildland fires.

Author Response

We appreciate the Reviewer's time and effort in reviewing our manuscript. Each of the comments and suggestions made by the Reviewer is addressed as detailed below.

Specific comments

1. Line 39: Perhaps provide a bit more detail as to why SWUIFT was used vs other fire models. My short read on this is that SWUIFT explicitly considers structure-to-structure fire whereas many fire models only consider fuel as natural vegetation.

Author Response

The reviewer is correct, we expanded the text to clarify the above comment:

"We subsequently use the wind fields extracted from WRF-LES at 15-minute intervals to drive the Streamlined Wildland-Urban Interface Fire Tracing (SWUIFT) model for urban fire spread (Masoudvaziri et al., 2021). **The SWUIFT model captures both near-field and far-field transport mechanisms of fire spread (i.e., radiation and fire spotting) between buildings and vegetation inside a community. SWUIFT is selected to simulate the fire spread considering that the fire ignition at Lahaina is close to the community (i.e., urban area) while well-established fire models have been developed with natural vegetation as the primary fuel.**"

2. Line 46: Agreed, and suppression would likely be highly unsuccessful given the extreme fire weather further motivating this modeling approach.

Author Response:

We edited the sentence considering the Reviewer's comment:

"The fire spread simulation does not consider the effects of structure hardening and suppression, **with the latter likely not a factor during the event given the extreme fire weather conditions.**"

3. Line 65: Are these sustained wind speeds or gusts? It might also be useful to remind readers that there are no good surface meteorological observations in the area that could be used for validation.

Author Response:

We thank the reviewer for allowing us to further explore this topic. The NWS and WMO define sustained winds to be over a 2-minute period. Our WRF outputs provide instantaneous winds at 15-minute intervals. Shown in Fig. R1 is a time series of the maximum 10-meter winds within a box over the Lahaina domain, with the solid black line showing the instantaneous winds and the dashed red line showing the smoothed winds, using a bi-directional 5th order Butterworth filter with a span of 5 data points (this is similar to a centered time-average and preserves the location of max/min).

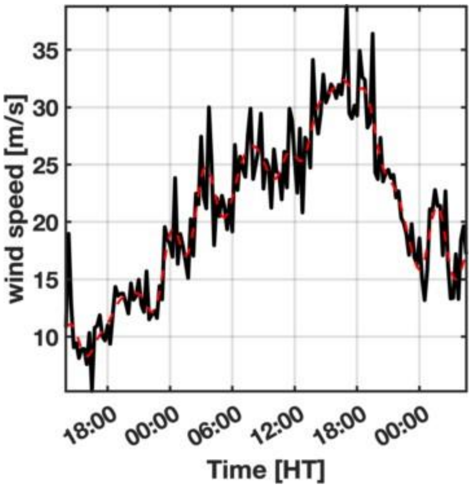

Figure R1: Time series of the maximum 10-meter winds within a box over the Lahaina domain

Fig. R1 suggests that sustained winds >35 m/s occur only for short time periods, whereas a longer time period of sustained winds >31 m/s is modeled. Moreover, in Fig. R2, we show a plan view of 10-meter wind speeds over the town of Lahaina over the duration of the simulation (culminating at 14:30 UTC).

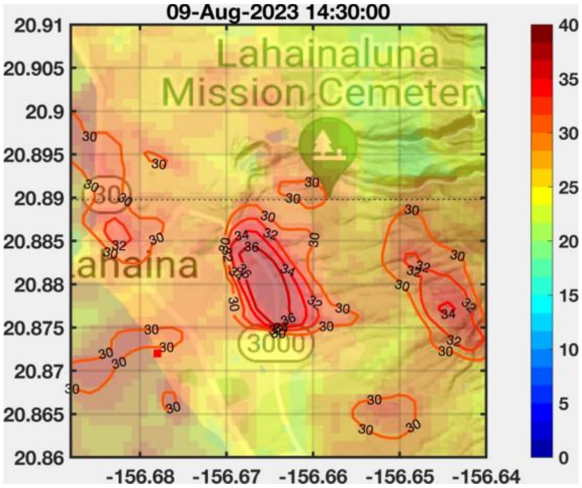

Figure R2: Plan view of 10-meter wind speeds over the town of Lahaina over the duration of the simulation (culminating at 14:30 UTC**)**

Fig. R2 suggests that the area of sustained winds >35 m/s is confined to the ignition region, and the town of Lahaina experienced sustained winds of ~30 m/s. Guided by these results, we modify the manuscript text as follows:

"The resulting downslope windstorm places the strongest winds **(>35 m/s)** 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 **sustained** winds of **30-35 m/s** affect **much** of the town, likely accounting for the video and photographic documentation of downed trees and powerlines along with structure damage prior to the fire's arrival. **Unfortunately, there are no known wind observations within the region of interest with which to compare these simulated results.**"

"Although further systematic studies are essential to improve simulation accuracy and validate with the actual fire behavior **and wind speeds**, the results presented herein demonstrate our ability to characterize reasonably well the disaster that transpired on the evening of August 8, 2023, in Lahaina."

4. Line 95: Is there value in comparing the final footprint of the areas burned in the modeling runs to estimates from remote sensing?

Author Response:
We have included a new figure and a few lines of text comparing the simulated fire spread until 8:30 PM and the observed final perimeter of the fire. Future work will extend the fire spread simulation and provide a quantitative assessment of the model performance.

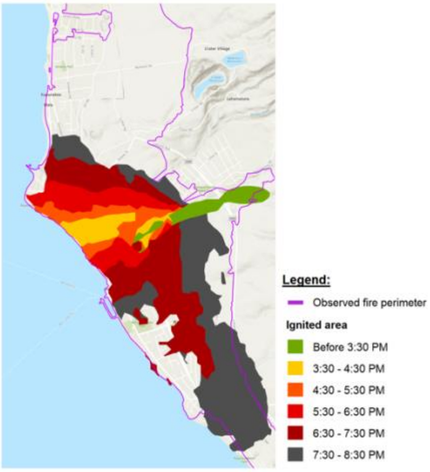

Figure 3: Fire perimeters from SWUIFT simulation at 1-hour intervals compared against the observed final fire perimeter

"**Fig. 3 shows the fire perimeters predicted by the SWUIFT simulation at 1-hour intervals until 8:30 PM against the final fire perimeter reported after the incident (Pacific Disaster Center, 2023). Most of downtown Lahaina and the impacted area to the south is ignited by 8:30 PM. It can be hypothesized that the fire continued to spread to the north after 8:30 PM**."

Added reference:
Pacific Disaster Center. (2023). *Damage Assessment Release as of 8/17/2023*.
https://www.pdc.org/maui-wildfire/ (accessed November 2023).