“The Community Fire Behavior Model for coupled fire-atmosphere modeling: Implementation in the Unified Forecast System” by Pedro A. Jiménez y Muñoz, Maria Frediani, Masih Eghdami, Daniel Rosen, Michael Kavulich, and Timothy W. Juliano.

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Reviewer #3

Review for "The Community Fire Behavior Model for coupled fire-atmosphere modeling: Implementation in the Unified Forecast System" The manuscript introduces the Community Fire Behavior Model (CFBM), a newly developed fire behavior model designed for seamless coupling with different atmospheric models using the Earth System Modeling Framework (ESMF). The key objective of CFBM is to provide a flexible and modular framework for simulating coupled fire-atmosphere interactions without requiring model-specific interpolation procedures. This approach is intended to foster broader collaborations and model integrations beyond the traditional Weather Research and Forecasting (WRF) model with fire extensions (WRF-Fire). The current review starts with specific comments in each section of the manuscript and finishes with a general comments section, followed by a final decision section.

RESPONSE

We would like to thank this reviewer for the time she/he devoted to reviewing the manuscript and for the comments provided that have helped to increase the quality of the manuscript. Below we reproduce the comments, followed by a detailed answer that includes the changes introduced in the manuscript. These include, among other things, running new simulations with a more similar setting of WRF-Fire and UFS-CFBM (same set of parameterizations, time step, and number of vertical layers), adding quantifications of the agreement between the simulations, adding an idealized case study, and checking for consistency in the simulations in sensitivity experiments. We believe the manuscript should be appropriate for publication this time.

COMMENT 1

The fire behavior model:
The input data interface remains dependent on Geogrid from WPS, which necessitates pre-processing via WRF. Consider addressing whether the model can be decoupled from WRF-specific tools.

RESPONSE

The CFBM relies on the WRF Preprocessing System (WPS) in this first implementation but could be decoupled from WPS. Indeed, our plans are to go beyond WPS in future versions of the model. Although WPS was originally developed for WRF, its reliability, parallelization, and flexibility to manage output variables via namelist or tables make it appropriate for using it for other models. Actually, it is already being used by other models. For example, it is used by the Energy Research and Forecasting (ERF, Almgren et al. 2023), and the Model for Prediction Across Scales (MPAS, Skamarock et al. 2012). This last one, MPAS, will be incorporated into UFS and thus WPS will not make an extra requirement for the UFS-CFBM coupling.

Also, relying on WPS in this initial version of the CFBM helps to ensure consistency with WRF-Fire, a major objective in this manuscript, since both models rely on the same preprocessing system. We have clarified in the new version of the manuscript that it is expected that future versions of the CFBM will not rely on WPS "*In the current version of CFBM, we also rely on the Geogrid program to define the fire grid and interpolate the static datasets, but, since there is no atmosphere component, only the fuels, and elevation (including slopes) in the fire grid are used. It is expected that future versions of CFBM will have its own preprocessing system.*"

COMMENT 2

The results could benefit from improvements to the fire initialization since the method presented seems to mismatch fire and atmosphere dynamics. The authors should consider using a spin-up period during the perimeter initialization.

RESPONSE

We use the same fire initialization procedures in UFS-CFBM and WRF-Fire to check for consistency between results of both fire behavior models. The initialization procedure we use is the only option available in WRF-Fire. This methodology has been successfully used in previous research and thus supported by publications (e.g., DeCastro et al. 2022; Turney et al. 2023). We understand there are other initialization methods that can be explored in future versions of the CFBM (e.g., Kochanski et al. 2023) where our intention will be to go beyond current WRF-Fire methods. We clarified these aspects in the new version of the manuscript when describing the fire initialization methods: "*This fire-perimeter initialization method is the only available in WRF-Fire and has been successfully used in previous research with the WRF-Fire model (DeCastro et al. 2022; Turney et al. 2023). More sophisticated methods (Kochanski et al. 2023) could be explored in future versions of the model that will go beyond WRF-Fire methods.*"

The simulations we present in the paper starting from an observed perimeter are one way simulations in order to compare with the simulation we performed with the standalone version of CFBM that reads WRF data offline. The fire and atmospheric dynamics do not play a role here. This experiment aims to check for the consistency of UFS and WRF-Fire when starting from a given fire perimeter, and our results show this consistency.

The perimeter initialization runs have a spin-up period. This information was missing in the previous version of the manuscript. We have added the information: "*This leaves 2.7 h of spin up for the Perimeter-1 runs and 0.9 h for the Perimeter-2 runs*".

COMMENT 3

The two available options for fire wind interpolation require further explanation. Additionally, if wind reduction factors are applied, their implementation and rationale should be discussed.

RESPONSE

We have improved our explanations: "*Two interpolation options are available. The first one uses a linear interpolation on the logarithm of height from two adjacent model layers to the target height. In the second one, the user specifies a second height and the interpolation is performed from this height to the target height using the logarithmic wind profile.*". These are the options available in WRF-Fire. There are no wind adjustment factors (WAF) for the moment in CFBM since we follow WRF-Fire methods in our current implementation. We are currently exploring the option of adding WAFs (Eghdami et al., 2025). We have clarified this too: *In the future, we would like to alleviate this subjective choice and implement the use of wind adjustment factors to automatically identify the height that drives the fire evolution based on the fuel characteristics Eghdami et al. (2025).*"

COMMENT 4

The manuscript should specify whether Lambert-Conformal projection is the only supported coordinate system in CFBM. If additional projections are supported, this should be clarified.

RESPONSE

Yes, we agree, we have clarified this aspect: "*the WRF projection must be Lambert-Conformal in CFBM version 0.2.0. Support for Mercator and polar stereographic projections will be added in future versions.*".

COMMENT 5

Experimental setup:
The downscaling from a 3 km atmospheric grid to a 100 m fire mesh presents notable limitations:
- The atmospheric resolution is too coarse to adequately capture fire atmosphere interactions.
- The fire mesh resolution is also too coarse to properly resolve fire spread parameterizations.

RESPONSE

We used 3 km grid spacing for the atmospheric grid spacing because it is the one used in the UFS-based Rapid Refresh Forecast System (RRFS) but in the revised version of the manuscript we use 1 km grid spacing. This largely reduced the ratio of the atmosphere to fire grid size (10 in the current version of the manuscript). Going beyond this atmospheric grid spacing cannot be easily justified in UFS since we start to go into the “gray zone” or “terra incognita” region where is not clear how to parameterize turbulence effects; and it is not possible to use a large-eddy simulation (LES) approach in UFS currently (it is possible in WRF). Hence, we stay at 1 km grid spacing because it is at the limit of what is possible with UFS and it allows us to have similar model configurations to evaluate the consistency between UFS-CFBM and WRF-Fire which is the main objective of the manuscript. The feedback that we see from the fire to the atmosphere, although small, is consistent between UFS-CFBM and WRF-Fire (Fig. 10 with the time series of the fluxes, and Figs. 11-14 with the feedback to the atmosphere). Hence, the configuration is sufficient to support the conclusions of the manuscript.

We have incorporated the previous rationale in the new version of the manuscript: “*The simulations were configured with a single domain covering the state of Colorado at 1 km horizontal grid spacing. The WRF domain has 629 by 599 grid points whereas the UFS domain has 599 by 570 grid points. Although going to finer grid spacing is desirable to better represent fire-atmosphere interactions using a turbulence resolving mode based on large-eddy simulation (LES), this is not possible with UFS that currently lack a LES approach. Hence, we used 1 km because is at the limit of what can be achieved with traditional planetary boundary layer parameterizations available in both UFS and WRF since going beyond 1 km goes into the "gray zone" or "Terra Incognita" (Wyngaard, 2004) where turbulence starts to be explicitly resolved, and thus not easy to parameterize*.”

Having 100 m grid spacing on the fire grid only affects the elevation and fuel representation. We can see on Figure 4 that the fuels are mostly two fuel classes, category 8, closed timber litter, and no-fuel, and cover large regions well represented by the 100 m spacing. Elevation is more heterogeneous, but at 100 m we will resolve the most important terrain features. So 100 m captures the main heterogeneities over the region. In any case, the important aspect of our experimental design is to have as close as possible configurations in UFS-CFBM and WRF-Fire to check for consistency of the results from both models and this is possible using 100 m grid spacing in the fire grid of both models. Indeed both models have similar elevations and the fuel types since both models use Geogrid to initialize the fire grid. We now say: “*Hence, both UFS and WRF use a fire domain of 100 m grid spacing which is sufficient to capture the main heterogeneities in fuels and elevation over the region. The fuel and elevation data are generated by Geogrid in both models which is desirable for our main purpose of checking consistency between both models.*”

COMMENT 6

The rationale behind different configurations between WRF and UFS regarding vertical layers and time steps should be justified. For instance, the use of different number of vertical layers and time steps?

RESPONSE

The reviewer is right. In the new version of the manuscript we use the same number of vertical levels (65) and the same time step (4 s) for both the atmosphere and the fire model in order to have WRF and UFS configured as close as possible. For the same reason, we also use the same set of parameterizations. We introduced changes to explain these aspects in the new version of the manuscript (see changes in Section 4.1.).

COMMENT 7

Validation:
Adjusting wind height to better match fire progression raises concerns about the validity of the model's predictive capability. It should be clarified whether this adjustment is an empirical correction or an inherent part of the modeling approach.

RESPONSE

In the new version of the manuscript we do not need to adjust the height of the winds in UFS. The differences were originated by the treatment of the land use in WRF and UFS that caused a discrepancy in the roughness length which largely determines the magnitude of near surface winds. We now use the same land surface model and the roughness lengths are in better agreement between WRF and UFS. This leads to better agreement of the simulated winds. The correlation, bias, and mean absolute error between the wind speed from UFS and WRF is 0.69, -0.3 m/s, and 0.5 m/s, respectively. This is a decent agreement considering UFS and WRF use different dynamical cores. See the new Figures 7 and 9 and their related discussion.

COMMENT 8

The similarity of results between one-way and two-way coupling suggests that the two-way coupling mechanism has not been adequately validated. Further evidence of feedback interactions is needed.

RESPONSE

The feedback from the fire to the atmosphere in UFS-CFBM and WRF-Fire is small but there is consistency between the two models as exemplified by the time series of the winds (Figure 9) and fluxes (new Figure 10); the heat flux, temperature, and humidity in the atmospheric grid (new Figs. 11-13); and new in the new version of the manuscript, the vertical velocity (Fig. 14) which is further evidence of feedback interactions. WRF-Fire is widely used and it has been extensively validated, and UFS-CFBM produces impacts in the atmospheric grid of similar magnitudes. In the new version of the manuscript we use 1 km grid spacing in the atmospheric grid and we also see similarities between two-way and one-way simulations in both models, WRF and UFS. This suggests that going to even small scales to explicitly resolve turbulence would be necessary to better capture the fire-atmosphere interactions. We recognize that this is desirable but it is not possible in UFS (see answer to comment 5). However, this is fine for our experimental design that focuses on ensuring consistency between WRF-Fire and UFS-CFBM. To this end, we show the agreement of the time series of the fire fluxes in the fire grid (new Fig. 10) and in the atmospheric grid (Figs. 11-14). These figures show that the feedback from the fire to the atmosphere is consistent between WRF-Fire and UFS-Fire. We show in Figure 11 the magnitude of the heat flux in the atmospheric grid and how this is, as expected, increasing the 2 m temperature (Fig. 12) and the vertical velocity (Fig. 14). Results for the impacts in the vertical velocity have been added to provide further evidence of the feedback interactions. Again both models are in sufficient agreement to suggest that the feedback is well implemented.

COMMENT 9

The validation would benefit from quantitative evaluation metrics such as the Jaccard index or Sørensen–Dice coefficient to assess model performance systematically.

RESPONSE

Yes, we agree that it is good to have quantitative metrics and we have added them to the new version of the manuscript. We have calculated the Heidke skill score and the Sorensen coefficient. Both show similar results. In the new version of the manuscript we show results for the Heidke skill score comparing the results from UFS-CFBM and WRF-Fire, as well as CFBM and WRF-Fire (Fig 1 of this document, and Fig. 6 in the new version of the manuscript). We focus on the comparison of the simulated results because in the manuscript we focus on the model-intercomparison to ensure the consistency of our implementation. The Heidke skill score is always larger than 0.8 which is large. We have added text in the new version of the manuscript to introduce the figure and support the visual comparison of results.

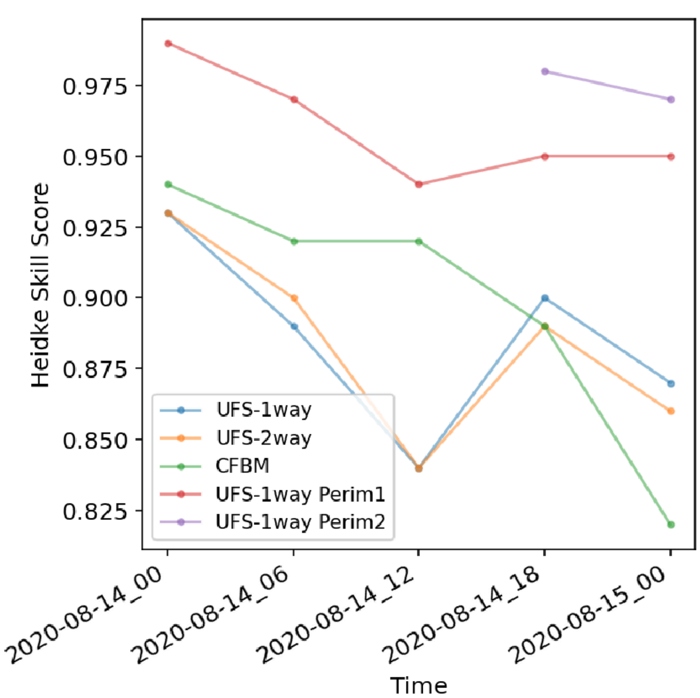

Figure 1: Heidke skill score comparing the simulated perimeters from UFS to the WRF-Fire results. The simulation labelled as CFBM is the standalone run driven by WRF data and has been compared against WRF-Fire results

COMMENT 10

While the manuscript acknowledges underestimating fire spread in some regions and overestimating in others, it does not provide sufficient explanation for these discrepancies. A sensitivity analysis on parameter uncertainties (e.g., fuel properties, and wind corrections) would strengthen the discussion.

RESPONSE

We have redone the simulations using the same set of parameterizations, the same time step, and the same number of vertical layers. We have also quantified the agreement of the simulated fire areas using the Heidke skill score (see Fig. 1 of this document and the answer to comment 9 above). We describe the discrepancies and provide some explanations such as the presence of barriers not accounted for by the model, portions of the fire perimeter does not seem to be active but in the model the whole perimeter is considered active, and potential issues in the timestamps of the fire perimeters. It is not our objective to evaluate the simulation against observations beyond fire perimeters to characterize/improve the realism of the simulation. That is the logical next step. Herein we focus on the model intercomparison to inspect the adequacy of our implementation.

We did run sensitivity experiments as suggested. We performed sensitivity experiments to the height used to drive the fire evolution and to the fuel moisture content. Results are summarized in Figure 2 of this document that shows the evolution of the burnt area. We see the expected sensitivities, a faster propagation when the fuel moisture content is reduced or the height of the winds is increased. The more important aspect to highlight is the consistency between UFS-CFBM and WRF-Fire results.

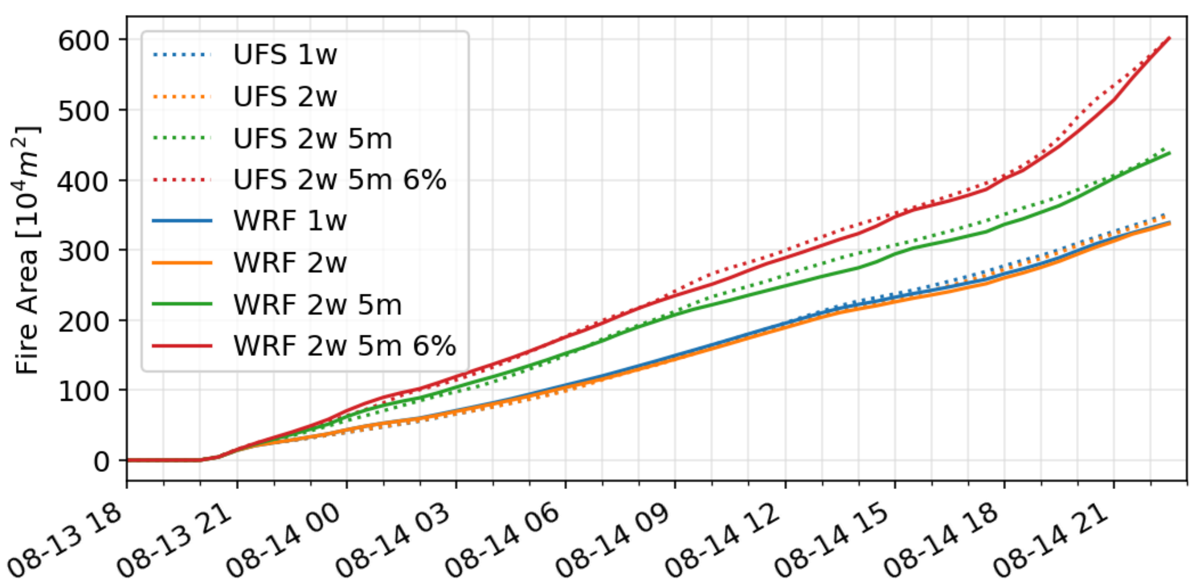

Figure 2: Evaluation of the size of the burnt area as a function of time for several experiments using WRF-Fire and UFS-CFBM. See legend for the description of the experiments.

COMMENT 11

Other Minor Comments:
Line 156: The phrase "substantial portions of new code" requires further clarification regarding the specific novel contributions.

RESPONSE

WRF-Fire code is mostly confined to the physics directory in Figure 1. And even this code has been largely modified to eliminate atmospheric dependencies and other parts of the code not needed. There are some WRF subroutines in other directories that we modified from WRF, but the majority outside the physics directory is new code. We have clarified this in the new version of the manuscript: "*The WRF-Fire methods are mostly confined to the physics directory (Fig. 1). We have reorganized, modified and added substantial portions of new code (mostly in the directories not labelled as physics in Fig. 1) to create a standalone fire model,...*"

COMMENT 12

Line 166: The term "atmospheric dependencies" is ambiguous and requires clarification.

RESPONSE

Yes, we now say: *"In addition, all the code related to WRF's atmosphere has been removed from the fire code in the physics directory. This includes removing procedures to interpolate atmospheric variables from the atmospheric grid into the fire grid."*

COMMENT 13

Lines 166-167: The phrase "the WRF grid to the WRF-Fire grid" is misleading, as both the atmospheric and fire grids are components of WRF-Fire.

RESPONSE

Yes, we now say: "*This includes removing procedures to interpolate atmospheric variables from the atmospheric grid into the fire grid.*"

COMMENTS 14 and 15

Lines 167-168: The statement "The calculation of the fire grid latitude and longitudes..." appears misplaced within the section.

Lines 168-169: The manuscript does not adequately describe the improved approach for geolocation determination or how it enhances accuracy.

RESPONSE

We have modified the sentence related to the geolocation of the fire grid to better connect it to the previous one. We have clarified that we use parameters of the map projection to calculate the fire geolocation just as the geolocation of the atmosphere is done: "*In addition, all the code related to WRF's atmosphere has been removed from the fire code in the physics directory. This includes removing procedures to interpolate atmospheric variables from the atmospheric grid into the fire grid. The interpolation procedures were used to interpolate the latitudes and longitudes from the atmosphere into the fire grid, and we now calculate the geolocation of the fire grid using the map projection information just as the atmospheric grid geolocation is calculated.*"

COMMENT 16

Line 174: The methodology for handling grid mismatches and specifying the fire domain should be explicitly detailed.

RESPONSE

Yes, this was missing in the previous version of the manuscript. We have clarified this: "*The standalone model does not need the fire grid, specified by the Geogrid output, to match the WRF domain. The only requirements are the fire grid included within the WRF domain, and the WRF simulation to have certain variables available. The interpolation of variables from the WRF atmospheric data into the fire grid uses a nearest-neighbour interpolation. We plan to include other interpolation methods in future versions of the model.*"

COMMENT 17

Line 176: … the three-dimensional horizontal wind components (U and V variables in WRF).

RESPONSE

Yes, this is correct, we have introduced this change.

COMMENT 18

General Comments:

The manuscript presents limited innovations in fire physics, appearing to largely replicate WRF-Fire, with minor modifications following Mandel et al. (2011) and Munoz-Esparza et al. (2018). The novelty of the contribution should be better articulated.

RESPONSE

The main novelty of our contribution is to develop, for the first time, a fire behavior model that is available for coupling to atmospheric models via the ESMF library. Using ESMF largely simplifies the coupling of the atmosphere to the fire modules. Indeed, the ESMF library is a standard approach used to couple Earth system components. There is no other fire behavior model with this functionality. We highlight this in the abstract: "*with this aim, we have created, for the first time, a fire behavior model that can be connected to other atmospheric models without the need of developing specific low-level procedures for the particular atmospheric model being used.*". We say this in the introduction: *"Herein we present, for the first time, a fire behavior model implemented as a NUOPC to facilitate its coupling with other atmospheric models"*. We now highlight the originality in the conclusions as well: *"CFBM is the first fire behavior model available for coupling via the ESMF library."* We believe this originality is appropriate for our model description manuscript. And our results show the consistency of WRF-Fire and UFS-CFBM which supports the adequacy of our implementation. WRF-Fire methods will be enhanced in future versions of the model.

Also, UFS did not have a fire behavior model and UFS users are able for the first time to perform coupled atmosphere-fire behavior simulations. We present here, for the first time, fire behavior simulations based on the UFS model. We have highlighted this in the conclusions: "*The CFBM has been coupled to UFS and this allowed us, for the first time, to perform fire behavior simulations with UFS*."

COMMENT 19

The study is restricted to a single fire event (Cameron Peak Fire), which limits the generalizability of the findings. Expanding the analysis to multiple fire events with varying topographies and meteorological conditions would improve the robustness of the conclusions. If additional events cannot be incorporated, at a minimum, a sensitivity analysis should be conducted.

RESPONSE

One fire case is sufficient to check for consistency between WRF-Fire and UFS-CFBM, our main purpose here. We do show sensitivities to the point versus perimeter initialization, and to one versus two way feedback. And we simulate different phases of the fire. In all of the runs and sensitivity experiments we see consistency between both models. See the Heidke skill score and related discussion above (Fig. 1, and answer to comment 9).

The new version of the manuscript now includes a new section showing results for idealized fire simulations. This compares the simulation of the fire spread to the theoretical solution, and we found that it behaves as expected. See results and discussion in the new section 4.2.1.

We believe these results are sufficient to support the conclusions of the study focussed on the adequacy of our implementation and the consistency between WRF-Fire and UFS-CFBM.

We have also done sensitivity experiments to the fuel moisture content and to the height of the winds that drive the fire evolution. We also see consistent results between UFS-CFBM and WRF-Fire. See Fig. 2 above and related discussion in comment 10.

COMMENT 20

The computational trade-offs of coupling CFBM with other atmospheric models should be acknowledged and compared to existing solutions such as WRF-Fire.

RESPONSE

The main trade-off is the requirement of using the ESMF libraries to couple the atmosphere to the fire. This provides advantages, since the fire grid does not need to match the atmospheric grid. The fire grid could be much smaller reducing the computational cost. Also, it is possible to have any kind of atmospheric grid (e.g., unstructured) and ESMF will automatically perform the interpolation of variables from one grid to the other. We already indicated that ESMF is a requirement and now we have added: "…*the region covered by the fire simulation in CFBM does not need to match the atmospheric domain allowing for using smaller fire domains which reduces the computational requirements of the fire model. Also, it is possible to have any kind of atmospheric grid (e.g., unstructured) and the ESMF libraries will perform the interpolation of variables automatically.*". It also facilitates the maintenance of the code since the code of each component is isolated from the rest. The communication is done via the NUOPC cap of each component. We have improved our explanations of the NUOPC interoperability in Section 2.

COMMENT 21

Final Decision:
The manuscript is not recommended for publication mainly for the following reasons:
1. Misalignment with the journal's scope: The manuscript presents a well-structured refactoring of the WRF-Fire codebase to create a more modular and flexible fire behavior model. While the core fire physics remains largely unchanged, the restructuring enhances model interoperability, making it easier to couple with different atmospheric models using ESMF. This modularity is a valuable contribution to fostering broader collaborations within the fire modeling community. However, for this journal, which emphasizes advancements in geophysical modeling, the paper would benefit from further developments that go beyond code refactoring, such as improvements in fire physics or additional parameterizations. The reviewer

suggests submitting this manuscript to another journal with a different scope after resolving the issues in the following point.

RESPONSE

We would not downplay the novelty of having a fire behavior model available as NUOPC for coupling with other Earth System's components. It has not been done before and thus our work is original. Our contribution is incremental. This is a model description paper and from the aims and scope of the journal website we believe we align well with among other things "*Model description papers are comprehensive descriptions of numerical models which fall within the scope of GMD.*", or "*describe model components and modules, as well as frameworks and utility tools used to build practical modelling systems, such as coupling frameworks or other software toolboxes with a geoscientific application*"; and, again, we are original with our contribution because there is not a fire behavior model available for coupling as a NUOPC component.

COMMENT 22

2. Issues with validation methodology:
a. Discrepancies in model configurations (e.g., different vertical levels and parameterizations).
b. Inappropriate scales that likely weaken fire-atmosphere feedback.
c. Validation primarily relies on qualitative comparisons, which are insufficient for rigorous model evaluation.

RESPONSE

We now have very close model configurations including the same number of vertical levels, time step, and the same set of parameterizations which address the discrepancies raised. We have now increased the grid spacing to 1 km which is at the limit of what can be achieved with UFS. It is true that we see small impacts of the fire on the atmosphere, but the impacts are large enough to quantify the consistency between UFS-CFBM and WRF-Fire (Figs 9-14, with a new figure that compares the vertical velocity), the main goal of the manuscript. We have now added quantitative comparisons to go beyond qualitative aspects. For example, we provide the correlation, bias and mean absolute error for the agreement of the simulated wind speed and the simulated fluxes. And we have quantified the agreement between the simulated fire perimeters using the Heidke skill score (see Fig. 1 of this document and related discussion in the answer to comment 9).

COMMENT 23

A final recommendation is that instead of using a real-world fire case with significantly different configurations and scales between the coupled components, the authors should consider an idealized test case that allows for a more controlled and rigorous evaluation of the coupling framework.

RESPONSE

We have added a new section (Section 4.2.1) where we focus on an idealized case. The idealized case replicates the experiment we performed in our previous work with WRF-Fire (Munoz-Esparza et al. 2018) and illustrates that the more accurate the numerical method used to resolve the level set equation that tracks the location of the fire font, the more consistency with the theoretical solution. The results we obtained are in good agreement with our previous results with WRF-Fire (Munoz-Esparza et al. 2018) and contribute to illustrate the adequacy of our implementation in CFBM of WRF-Fire methods. Results are summarized in the new Figure 4 and its related discussion.

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