

All responses are in red.

#### General Comments:

This paper follows on from several recent publications that have focused on the development and use of the ARPS-Canopy model developed by Kiefer and colleagues. This new canopy model is a useful recent development, and is now being used to study the role of forest canopies in fire-atmosphere interactions. Fire-atmosphere interactions can significantly impact on wildland fire behaviour and therefore directly affect firefighter and civilian safety, so are of considerable importance.

This paper focuses on a specific application of ARPS-Canopy to look at the role of forest canopy gaps on fire to atmosphere interactions (note: no atmosphere to fire feedback is modelled). While this is an important topic that has received little prior consideration, I found the sensitivity analysis to be a little underwhelming. Of the simulations presented, consideration is primarily given to varying the forest canopy gap location relative to a time-invariant idealised representation of a low intensity fire. The sensitivity analysis reveals what in my opinion is fairly limited difference in the fire to atmosphere interaction between the four cases that include an idealised fire. As a result of this limited sensitivity, I also believe the authors need to be cautious in their conclusions. For example, the authors state, based on their results, that there is potential for forest canopy gaps to substantially affect the vertical and horizontal transport of heat away from the fire. I'm not certain that such a definitive conclusion can be drawn from this set of simulations. I am interested to know if the authors have results for a higher intensity fire, as these may show more pronounced sensitivity.

The current four-experiment study constitutes the initial phase of a larger study examining sensitivity of perturbations to canopy profile shape, fire intensity, and fire spread (e.g., backing vs. head fires). These items are included as future work at the end of the final paragraph of the manuscript (we have added fire intensity to the list). We have removed the qualifier "substantial" to avoid overstating the results (see your comment #16). Also, we have added a cautionary statement in the conclusions section about drawing conclusions from a limited number of experiments, with limited sensitivity.

The methodology seems to be generally robust for a sensitivity analysis of this kind. The various aspects of numerical model configuration are broadly in line with what I would expect. There is good spatial resolution in the forest canopy and the model top, while fairly low, seems reasonable. The one question I would ask the authors is to clarify how the inner and outer model domains interact at the boundary, and if there are any issues regarding the transfer of momentum and turbulent kinetic energy at these boundaries. It may be useful to include additional references, if any exist, to other applications of ARPS that have used a similar high resolution configuration. While the experiment design and analysis methodology seem appropriate, they are somewhat

limited in scope. The authors only consider the location of the forest canopy relative to the fire, and otherwise have an identical fire intensity and size.

For the inner model domain, we use time-dependent one-way lateral boundary conditions, that is, values of prognostic variables at the lateral boundary points of the inner domain are obtained from the outer domain simulation (updated every five minutes), but the outer domain simulation is completely independent of the inner domain simulation. For more information, please see the ARPS User's Guide (<http://arps.ou.edu/arpsdoc.html>). We have inserted "one-way lateral" where boundary conditions for the inner domain are first introduced in the text, to clarify the nature of the lateral boundary conditions. We are unaware of any issues with the transfer of momentum and TKE across lateral boundaries in ARPS. Other studies that have used ARPS with comparable spatial resolution include Dupont and Brunet (2008) and Michioka and Chow (2008) [note that the latter also used one-way nesting]. We have added these references to the text where the grid spacing is introduced. Regarding fire intensity experiments, see our response to your Scientific Significance comments (previous paragraph).

The paper is well written throughout and well structured. As this is a sensitivity analysis, many of the figures directly compare the same variables between simulations. However, due to the colours chosen for the contours and limited difference in variables between simulations, in a number of figures (e.g. Figs 2-7) it is difficult to clearly discern the key differences between simulations. Additionally, the colour bars shown in Figs 2-7 appear to me to be continuous, rather than discrete, which makes it difficult to properly determine the values in those plots. Figure captions are at times overly verbose and it could be useful to shorten where possible. In Figs 8-11, some of the labels are difficult to read due to their close proximity to the box and whisker plots. The labels are also given to two decimal points, which seems excessive.

Editor and reviewer note: We made changes to the manuscript in response to these comments during the access review stage:

[We experimented with different color schemes, and came to the conclusion that the blue->white->red color scheme is most ideal due to its simplicity and easy adaptability to each variable. However, we have reduced the number of shades in each plot to 12, to help the reader distinguish between shades, and we modified the color scheme so that values one interval either side of zero are shaded (i.e., no whitespace). We have also made the color bars discrete. Finally, the captions in Figs. 1 and 8 have been made less verbose, the positions of the labels in Figs. 8-11 have been adjusted to improve readability, and we now display only one digit to the right of the decimal point.]

Specific Comments:

Abstract:

1. "This study examines the impact of forest gaps on fire-atmosphere interactions" - it may be more appropriate to state that you consider only fire to atmosphere interactions,

as ARPS-CANOPY does not consider the atmosphere to fire feedback.

We appreciate your concern about our use of the term “fire-atmosphere interactions” to describe this study. Rather than use alternate wording like “fire to atmosphere interactions” we prefer to tone down the use of “fire-atmosphere interactions” in the text and be more specific about what we are examining in this study (changes were made, where appropriate, in the Abstract, Introduction, and Summary and Conclusions section). We have edited the second sentence in the abstract as follows:

OLD:

“This study examines the impact of forest gaps on fire-atmosphere interactions using the ARPS-CANOPY model...”

NEW:

“This study examines the influence of gaps in forest canopies on atmospheric perturbations induced by a low-intensity fire using the ARPS-CANOPY model...”

2. The final sentence of the abstract is a little off-topic relative to what is actually discussed in the paper.

We do not feel that the sentence in question is off-topic. This is a study of how gaps influence atmospheric perturbations above fires, and gaps fall under the broader heading of “forest heterogeneity”. We prefer to leave the sentence intact.

[No changes have been made to the manuscript in response to this comment.]

Introduction:

3. Line 81-85: Again it may be clearer to use the term “fire to atmosphere interactions” rather than “fire-atmosphere interactions”. The hyphen suggests to me that there is feedback in both directions.

Similar to our response to comment 1, we have edited the sentences on lines 81-85 as follows:

OLD:

“However, ARPS-CANOPY is suited to the specific goal of this study: examining how gaps in forest canopies impact fire-atmosphere interactions. Lastly, note that unlike Pimont et al. (2009) and Pimont et al. (2011), our focus is on fire-atmosphere interactions in general, and not the specific impacts of gaps on fire behavior. Furthermore, this study considers not only how fire-atmosphere interaction in forest gaps differs from the more studied homogeneous forest case, but also whether the ability of the fire to perturb the atmosphere is sensitive to the position of the gaps relative to the fire (e.g., upstream vs. downstream gap).”

NEW:

“However, ARPS-CANOPY is suited to the specific goal of this study: examining the influence of gaps in forest canopies on atmospheric perturbations induced by a low-intensity fire. Lastly, note that unlike Pimont et al. (2009) and Pimont et al. (2011), our focus is on fire-perturbed meteorological fields and not the specific impacts of gaps on fire behavior. Furthermore, this study considers whether the ability of the fire to perturb the atmosphere is sensitive to the position of the gaps relative to the fire (e.g., upstream vs. downstream gap).”

ARPS-CANOPY Overview:

4. Line 108-112: In these idealised simulations, does the day/night cycle affect the ground radiation budget as discussed here? I notice that the simulation is started at noon local time, so I wonder what effect this has on the simulations as they progress throughout the afternoon.

When performing a full-physics simulation, the day/night cycle does affect the ground radiation budget. However, for these idealized simulations, steady net radiation of  $520 \text{ Wm}^{-2}$  is applied at canopy top throughout the simulation. So, the diurnal cycle of net radiation has no effect on these simulations.

[No changes have been made to the manuscript in response to this comment.]

Model Configuration and Parameterization:

5. Line 134-135: If the Coriolis force is computed as a function of central latitude only, then what value for the central latitude is used? I’m assuming 40N based on details provided later. Is this term important for such a small model domain?

40° north latitude is specified (arbitrary); this detail has been added to the text. The term is likely negligible for the spatial and temporal scales considered herein, but was included nevertheless.

6. Line 143: Is there another term to describe a “rigid lid” upper boundary i.e. what kind of boundary condition is this? I’m not very familiar with the terminology of boundary conditions, so this comment may be ignored if appropriate.

The “rigid lid” upper boundary condition is equivalent to the “wall” lateral boundary condition. This is a fairly standard term (a Google search of “rigid lid upper boundary condition” returned 589 results).

[No changes have been made to the manuscript in response to this comment.]

7. Line 149-150: Can you briefly quantify or more clearly describe the stable stratification above 1 km?

The Brunt-Väisälä frequency,  $N$ , is  $0.013 \text{ s}^{-1}$ . This detail has been added to the manuscript.

8. Line 153-155: How do the authors determine that a quasi-homogeneous and quasistationary PBL has developed? Is there some numerical test based on TKE or some other variable?

We examined time series of mean temperature and wind speed within the outer domain, along with the standard deviation of these variables, and made a subjective assessment of quasi-stationarity (e.g., mean wind speed in the domain exhibits steady behavior after about 3 hours of model integration). Quasi-homogeneity was subjectively determined based on a review of horizontal cross-sections of mean temperature and wind speed.

[No changes have been made to the manuscript in response to this comment.]

Experiment Design:

9. Line 158: "Following a 30-minute spin-up period" - what is being spun-up for 30 min? Based on the previous paragraph, is this the spin-up period in the inner domain simulation once it is initialised (i.e. after 3 hours of outer domain simulation)?

ARPS requires that the child domain be initialized with zero subgrid-scale turbulence. The 30-min spin up period allows time for turbulence to develop. The first sentence refers to the 30-min spin-up period in the inner domain simulation (a 3-hour spin-up period is used in the outer domain simulation, as described in the last paragraph of Section 2.2).

[No changes have been made to the manuscript in response to this comment.]

Analysis Methodology:

10. Line 181-182: Do you mention at any point the frequency of the instantaneous wind components and temperature values e.g. is it every second or minute?

The instantaneous wind components are dumped out every second (i.e., 1 Hz frequency). This detail has been added to the text.

Mean Variable Analysis:

11. Figs 2-3: It would be useful to see wind vectors in the xz plane showing the u and w wind component wind vectors for the "with fire" simulations, to better show that clockwise circulation within the forest canopy. It is possible to discern it from Figures 2 and 3, but not as easily.

We agree that wind vectors would help the reader visualize the gap and fire-induced circulations. However, we put much effort into producing a modified Fig. 2 with the wind vectors overlaid and, unfortunately, found it impossible to prevent the figure from becoming too cluttered.

[No changes have been made to the manuscript in response to this comment.]

12. Line 220: “unstable boundary layer” I thought that a neutral static stability was used for the background? Or is there some local instability induced by the idealized fire?

A neutrally-stratified profile is used for the background state, however, net radiation of  $520 \text{ W m}^{-2}$  is applied at the canopy top (or ground surface in the gaps). This results in an unstable boundary layer. Information about the radiation flux was provided in the outer domain description in Section 3.2, but was unintentionally omitted from the inner domain description. This detail has been added to the manuscript to avoid misunderstanding.

13. Line 227 and previously: Acronym “SGS” is only used twice after it is first defined in paper. It may be simpler just to write subgrid scale each time, as its not a particularly intuitive acronym for some readers?

SGS has been replaced with sub-grid scale.

14. Line 239-240: I find it interesting that a superadiabatic lapse rate is evident given the background atmospheric conditions described in the methodology. It is also not specified in which direction the weak horizontal gradient in temperature goes. I think that some additional details could be useful here.

Regarding the presence of a superadiabatic lapse rate, see our response to comment #12. The sign of the horizontal temperature gradient (negative, i.e., temperature decreases from left to right) has been added to the text.

15. Line 244: “a 4% difference” - It might be clearer to state temperature difference as an absolute value rather than as a percentage change. I personally don’t have a good sense of what this 4% difference means.

The anomaly difference is 1.1 K. We have replaced “...about a 4% difference...” with “...a 1.1K (about 4%) difference...”.

16. Line 261: “potential to play a substantial role” - this statement seems too confident given the fairly limited difference between the gap and no gap cases.

In response to this comment, and your Scientific Significance comments, we have removed the word “substantial” from line 161 as well as the abstract.

#### Instantaneous Variable Analysis

17. Line 270: “the median is about 40% larger than in zone U” Again I would prefer to see absolute values rather than a percentage change. Or why not simply state the new median?

The difference in the median is  $0.2 \text{ m s}^{-1}$ . The absolute value is now included in the text.

18. Figures 8-11: It is not clear to me precisely why the outliers are calculated for these box and whisker plots with a maximum whisker length,  $w$ , of 1.5. I also think that the description of how the outliers are determined would be better placed in the main text, such as the methodology or results section, rather than at the bottom of an already verbose figure caption.

We used Matlab analysis software to generate the plots in this study. Matlab has a built-in box and whisker plot function that defines outliers as values that are more than  $w$  times the interquartile range away from the 25<sup>th</sup> ( $q_1$ ) and 75<sup>th</sup> ( $q_3$ ) percentiles [i.e.,  $q_3 + w*(q_3 - q_1)$  or  $q_1 - w*(q_3 - q_1)$ ]. In Matlab, the default value for  $w$  is 1.5. The documentation for this function states that “The default of 1.5 corresponds to approximately  $\pm 2.7\sigma$  and 99.3 percent coverage if the data are normally distributed.”

The description of the outlier methodology has been moved to the Analysis Methodology subsection, and the new detail about the choice of  $w$  (i.e.,  $\pm 2.7\sigma$  coverage) has been added to the text.

19. Line 283: There is no quantification of distribution width or skewness, so it depends only upon a visual inspection of the box and whisker plots. I think these statements would be better with some quantified data (e.g. standard deviation or skewness, both are easily calculated) to support them.

We have computed skewness and added the information to the text to better support our statements.

20. Line 285-286: “the effect of the gap on the median vertical velocity value is ambiguous” I wouldn’t say it is ambiguous, as you then describe the gap effects. Perhaps “inconsistent” would be a better word here?

“Ambiguous” changed to “inconsistent”.

21. Line 292-293: Conceptually, it’s not particularly clear to me why a reduced-drag region (i.e. forest canopy gap) would be considerably more turbulent than the surrounding forest. I would have expected the opposite e.g. winds high above the boundary layer tend to be more laminar due to the reduced effects of surface friction. Is it related to the concepts described in the mean analysis e.g. clockwise circulation developing within the canopy gap?

The drag force yields relatively weak mean wind speeds within the canopy, with a layer of pronounced vertical wind shear (and consequently, turbulence production) in the upper portion of the canopy. Deep within the canopy, any turbulence production and/or transport into that layer is countered by canopy drag. Removing the vegetation in a small area of the larger forest locally eliminates the canopy drag effect, allowing turbulence production and transport to

contribute to TKE without the canopy sink term.

[No changes have been made to the manuscript in response to this comment.]

#### Summary and Conclusions

22. Line 316: It might be useful earlier in the paper to compare  $25 \text{ kW m}^{-2}$  to a typical grass or forest fire, to give some physical sense of how intense the heating is.

We have added a sentence to compare  $25 \text{ kW m}^{-2}$  to values observed during low-intensity fire field campaigns (e.g., RxCadre). The value used herein is within the envelope of observed values and is considered representative of a low-intensity fire.

# A study of the influence of forest gaps on fire-atmosphere interactions

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**Abstract.** Much uncertainty exists regarding the possible role that gaps in forest canopies play in modulating fire-atmosphere interactions in otherwise horizontally homogeneous forests. This study examines the ~~impact of forest gaps on fire-atmosphere interactions~~ influence of gaps in forest canopies on atmospheric perturbations induced by a low-intensity fire using the ARPS-CANOPY model, a version of the Advanced Regional Prediction System (ARPS) model with a canopy parameterization. A series of numerical experiments are conducted with a stationary low-intensity fire, represented in the model as a line of enhanced surface sensible heat flux. Experiments are conducted with and without forest gaps, and with gaps in different positions relative to the fireline. For each of the four cases considered, an additional simulation is performed without the fire to facilitate comparison of the fire-perturbed atmosphere and the background state. Analyses of both mean and instantaneous wind velocity, turbulent kinetic energy, air temperature, and turbulent mixing of heat are presented in order to examine the fire-perturbed atmosphere on multiple time scales. Results of the analyses indicate that the impact of the fire on the atmosphere is greatest in the case with the gap centered on the fire, and weakest in the case with the gap upstream of the fire. It is shown that gaps in forest canopies have the potential to play a ~~substantial~~ role in the vertical as well as horizontal transport of heat away from the fire. Results also suggest that in order to understand how the fire will alter wind and turbulence in a heterogeneous forest, one needs to first understand how the forest heterogeneity itself influences the wind and turbulence fields without the fire.

## 1 Introduction

Wildland fires and the atmosphere interact across a range of spatial and temporal scales from macroscale ( $10^5$  -  $10^6$  m; hours to days) to microscale ( $10^{-3}$  -  $10^0$  m; seconds to minutes), and such interactions have been the subject of research for over a century [see Potter (2012a, b) for a review of the subject]. Studies of fire-atmosphere interactions have relevance for our understanding of (as well as modeling of) processes such as fire spread, smoke transport/dispersion, and tree mortality. Previous studies of fire-atmosphere interactions have mainly focused on horizontally homogeneous forests; the im-

30 pact on fire-atmosphere interactions of gaps or openings in otherwise homogeneous forests, whether natural (e.g., windstorm damage) or man-made (e.g. fuel breaks), remains largely unexplored. Furthermore, it is unclear how fire-induced atmospheric perturbations evolve as the fire progresses from forest to gap and back to forest. Note that the term “gap” is used in this study to denote clearings or overstory fuel breaks with horizontal dimensions of approximately one canopy height or larger, and not spaces between branches or between individual trees.

Before proceeding to discussion of the current state of knowledge of fire-atmosphere interactions inside forest gaps, some discussion of the simpler case of fire-atmosphere interactions in homogeneous canopies is warranted. The impact of homogeneous forest canopies on simulated fire-  
35 perturbed variables [e.g., temperature, turbulent kinetic energy (TKE)] and processes affecting such variables [e.g., turbulent mixing, shear production] was examined in Kiefer et al. (2015). In a series of numerical experiments within a homogeneous forest, the sensitivity of mean and turbulent flow downstream of a low-intensity surface fire to canopy density was examined. In general, near-surface turbulence both prior to and during the fire was reduced in the presence of a canopy. Both the fire-  
40 line normal component of wind and maximum vertical velocity were shown to be weaker with a sparse canopy than with no vegetation, although both variables were largely insensitive to further increases in canopy density. However, the influence of the fire on planetary boundary layer (PBL)-integrated vertical turbulent heat flux was greatest with a sparse canopy and gradually weakened with increasing canopy density.

45 With regard to fire-atmosphere interactions within gaps, although some modeling studies have examined fire propagation in discontinuous fuels beds (e.g., Linn et al., 2005), only Pimont et al. (2009, 2011) have examined in detail simulated fire-atmosphere interactions inside forest gaps. Pimont et al. (2009) examined the impact of a 180-m wide fuel break on mean and turbulent flow using the FIRETEC model (Linn and Cunningham, 2005) and simulated higher mean wind velocity and  
50 gust intensity inside the fuel break than in the surrounding forest, but reduced variability of wind direction in the break, relative to the surrounding forest. Pimont et al. (2011) used the FIRETEC model to examine the sensitivity of wind flow and fire propagation to structural parameters of a multiple grid-level forest canopy, including tree-cover fraction and clump size. Varying the structural parameters within a 200-m wide “treated zone” or fuel break and igniting a fire line upwind of the  
55 treated zone, the authors showed wind velocities to be stronger in the treated zone, relative to the surrounding forest, and found that the plume of hot gases was most strongly tilted from vertical when the fireline was inside the treated zone.

Studies that focus on flow within forest gaps in the absence of fire are somewhat greater in number (e.g., Bergen, 1975, 1976; Schlegel et al., 2012, 2015; Queck et al., 2015), though still small relative  
60 to the number of studies of flow within homogeneous forests and orchards (e.g., Shaw and Schumann, 1992; Raupach et al., 1996; Watanabe, 2004; Dupont and Brunet, 2008; Dupont and Patton, 2012a, b; Kiefer et al., 2015) and near forest edges (e.g., Patton et al., 1998; Lee, 2000; Dupont and

Brunet, 2007, 2009). Studies of flow within forest clearings or gaps consist primarily of field experiments (e.g., Bergen, 1975, 1976; Queck et al., 2015) and large-eddy simulation (LES) modeling (e.g., Schlegel et al., 2012, 2015; Queck et al., 2015). Analysis of field experiment data and LES modeling results in Queck et al. (2015) showed the impact of small inhomogeneities such as forest clearings on not only turbulent flow but also mean flow within the canopy. A recirculation zone was simulated with the LES model, consistent with other LES studies of flow in forest clearings (e.g., Schlegel et al., 2012, 2015), which was confirmed by companion field experiments, but was not reproduced in companion wind tunnel experiments and Reynolds Averaged Navier Stokes (RANS) modeling. The recirculation zone was found to be largely confined to the clearing, with the influence of the clearing on mean flow quickly diminishing with height above the canopy.

In this study, we use the ARPS-CANOPY model (Kiefer et al., 2013) to explore the sensitivity of fire-perturbed atmospheric variables (e.g., air temperature, turbulent kinetic energy) to the presence of gaps in the forest cover. ARPS-CANOPY is a modified version of the Advanced Regional Prediction System (ARPS) model (Xue et al., 2000, 2001) in which the effects of vegetation elements (e.g., branches, leaves) on drag, turbulence production/dissipation, radiation transfer, and the surface energy budget are accounted for through modifications to the ARPS model equations. ARPS-CANOPY was primarily developed for low-intensity fire applications, wherein transport and dispersion of smoke are especially sensitive to local vegetation, and has been applied to simulations of real-world prescribed fires in heterogeneous forest canopies (Kiefer et al., 2014) and idealized low-intensity fires in homogeneous forest canopies (Kiefer et al., 2015). Note that due to limitations of ARPS-CANOPY, this study does not directly address the impact of forest gaps on processes such as fire spread and tree injury. However, ARPS-CANOPY is suited to the specific goal of this study: examining how the influence of gaps in forest canopies impact fire-atmosphere interactions on atmospheric perturbations induced by a low-intensity fire. Lastly, note that unlike Pimont et al. (2009) and Pimont et al. (2011), our focus is on fire-atmosphere interactions in general fire-perturbed meteorological fields, and not the specific impacts of gaps on fire behavior. Furthermore, this study considers not only how fire-atmosphere interaction in forest gaps differs from the more studied homogeneous forest case, but also whether the ability of the fire to perturb the atmosphere is sensitive to the position of the gaps relative to the fire (e.g., upstream vs. downstream gap).

The remainder of this paper is organized as follows. A description of the model and experiment design are included in Section 2, including a brief overview of the ARPS-CANOPY model and how it differs from the standard ARPS model (2.1), a description of the model configuration and parameterization (2.2), and a summary of the experiment design (2.3). Results and discussion of the sensitivity experiments are presented in Section 3, beginning with a brief summary of the analysis methodology (3.1), followed by analysis of mean (3.2) and instantaneous (3.3) variables. Finally, the paper is concluded in Section 4.

## 2 Model description and numerical experiment design

### 100 2.1 ARPS-CANOPY Overview

The development of ARPS-CANOPY is described in detail in Kiefer et al. (2013); the following is a brief summary. For validation of ARPS-CANOPY in orchard and forest environments, see Kiefer et al. (2013) and Kiefer et al. (2014), respectively.

105 First, modifications to the ARPS model equations were made to account for the drag force of vegetation elements, via a drag force term added to the momentum equation, and the enhancement of turbulence dissipation in the canopy air space, via a sink term added to the sub-grid scale (~~SGS~~) turbulent kinetic energy (TKE) equation (Dupont and Brunet, 2008). Note that although multiple turbulence schemes are available in ARPS, ARPS-CANOPY exclusively utilizes the 1.5 order TKE-based turbulence closure (Deardorff, 1980; Moeng, 1984).

110 Subsequently, Kiefer et al. (2013) modified ARPS-CANOPY to allow for simulation of non-neutral canopy flows. Specifically, a term was added to the thermodynamic equation to represent heating (cooling) of the canopy air spaces resulting from the vertical flux convergence (divergence) of net radiation intercepted by the canopy, and the ground radiation budget was modified to account for shading of the ground surface by the overlying vegetation during the day and reduction of outgoing longwave ground radiation at night. As an alternative to computing the radiation budget at all grid points within the canopy, a net radiation profile was employed that decays downward from canopy top as a function of the cumulative leaf area index (computed from the top of the canopy downward) and an empirically determined extinction coefficient [0.6 in this study, as in e.g., Kiefer et al. (2013); Dupont and Brunet (2008)]. Computation of the net radiation budget at canopy top is otherwise  
115 identical to the standard ARPS ground radiation budget, except ~~a constant value~~ constant values of albedo appropriate for ~~forested areas is forest and gap are~~ utilized (0.1 and 0.3, respectively), and the outgoing longwave component is computed as a function of air temperature at canopy top, rather than skin temperature. Lastly, a production term was added to the ~~SGS-sub-grid scale~~ TKE equation to represent turbulence production in the wakes of canopy elements.

125 It is important to note that ARPS-CANOPY does not resolve the flow around individual trees or the heating/cooling of individual branches or leaves. In all aspects of the model, the canopy is represented as a height-varying plant area density profile ( $A_p$ ), specified at each grid point.  $A_p$ , defined as the one-sided area of all plant material per unit volume of canopy, is a bulk measure of the density of a large group of trees. It is also important to note that aside from the modifications  
130 outlined here, ARPS-CANOPY is otherwise identical to standard ARPS.

### 2.2 Model configuration and parameterization

As stated in the previous section, a 1.5-order subgrid-scale turbulence closure scheme with a prognostic equation for TKE is utilized. Radiation physics following Chou (1990, 1992) and Chou and

Suarez (1994) are applied outside of the canopy, with the parameterization outlined in Section 2.1  
135 applied at points inside the canopy. Moist processes are represented in the model, with Lin ice micro-  
physics (Lin et al., 1983) and explicit convection enabled. Fourth-order accurate finite differencing  
of the advection terms is used in both the vertical and horizontal directions. The Coriolis force is  
computed (as a function of central latitude only (arbitrarily specified as 40° N)).

A 1-way nesting procedure is utilized with two three-dimensional computational domains, and  
140 a periodic boundary condition is applied at the lateral boundaries of the outer domain. The outer  
domain consists of 153 x 103 x 78 grid points (including points used only for boundary condition  
calculations), with 50 m horizontal grid spacing; the inner domain, centered within the outer domain,  
consists of 99 x 51 x 78 grid points, with 10 m horizontal grid spacing. Vertical grid spacing of 2 m is  
utilized in both domains, up to a height of 84 m, above which vertical stretching is applied. Note that  
145 ARPS and ARPS-CANOPY have been applied in previous studies with horizontal and vertical grid  
spacing O(10 m) or smaller (e.g., Michioka and Chow, 2008; Dupont and Brunet, 2008). With this  
vertical grid structure, there are 9 grid points at or below the canopy crown (canopy height is 18 m).  
The top of both model domains is at 3 km, with a rigid lid upper boundary condition and a Rayleigh  
damping layer in the uppermost 1 km to prevent reflection of waves from the upper boundary.

150 The outer domain simulation is initialized at noon local time, with a uniform net radiation flux of  
 $520 \text{ Wm}^{-2}$  applied at the canopy top to represent daytime heating typical of 40° N latitude in early  
spring. The outer domain simulation is run with a uniform canopy (see Section 2.3) and no fire, and  
is initialized with a base state sounding consisting of uniform wind speed ( $2.5 \text{ ms}^{-1}$ , westerly) from  
the surface to domain top and neutral static stability below  $z = 1 \text{ km}$  (~~stable stratification above~~)  
155 [stable stratification ( $N = 0.013 \text{ s}^{-1}$ ) above]. Although the model is initialized with a horizontally  
homogeneous atmosphere, a random perturbation of magnitude 1 K is applied to the potential tem-  
perature field at the initial time (at all model levels) to promote the development of 3D turbulent  
structures. The outer domain simulation is run for a total of four hours; after approximately three  
hours a horizontally quasi-homogeneous and quasi-stationary PBL develops, and the inner domain  
160 simulation is initialized at that end of hour three. The inner domain simulation is run for one hour,  
with uniform net radiation flux applied as in the outer domain simulation (except applied at the  
ground surface in gaps), with one-way lateral boundary conditions updated every five minutes.

### 2.3 Experiment design

Following a 30-minute spin-up period, a  $25 \text{ kWm}^{-2}$  surface turbulent sensible heat flux, representa-  
165 tive of a low-intensity fire, is applied within a 50-m wide north-south strip positioned 3.2 km down-  
stream of the western boundary of the inner domain. ~~The heat~~ This value was chosen to fall within the  
envelope of 1-min mean vertical turbulent heat fluxes reported during field studies of low-intensity  
fires [8-155  $\text{kWm}^{-2}$  (e.g., Clements et al., 2007; Hiers et al., 2009; Heilman et al., 2013)]. The strip  
extends the length of the domain in the y-direction (500 m), and the heat flux is applied for 30

170 minutes. The heat from the fire is laterally distributed across the strip in a step pattern, with 85% of the total heat flux ( $21.25 \text{ kWm}^{-2}$ ) applied at the center grid point, and the fire-induced heat flux in the flanking cells stepping down to zero three cells away. Recall from the previous section that a  $2.5 \text{ ms}^{-1}$  westerly base state wind is applied in all simulations; therefore, the ambient wind is perpendicular to the fireline.

175 The portion of the domain surrounding the fire line is divided into three zones, delineated by their position relative to the fire center: **Upstream**, **Center**, and **Downstream** (Fig. 1). Four canopy configurations are considered in this study: uniform canopy with no gaps (case NG), gap in the upstream zone (UG), gap in the center zone (CG), and gap in the downstream zone (DG); for all gap experiments the gap is 50 m (5 grid points) wide. A summary of the canopy gap configurations is provided in Fig. 1a, along with the  $A_p$  profile used in all experiments, and a vertical cross-section of  $A_p$  in the x-z plane is provided in Fig. 1b (case CG only). Note that within the forest blocks the canopy is horizontally homogeneous and represented by a single  $A_p$  profile, and within the gaps  $A_p$  is zero; the resulting  $A_p$  cross-section (Fig. 1b) is similar to case HOM in Schlegel et al. (2012). The vertical canopy profile is characterized by a moderately dense overstory ( $\max A_p = 0.455 \text{ m}^{-2}\text{m}^{-3}$ ), and an open trunk space with sparse understory ( $\min A_p = 0.006 \text{ m}^{-2}\text{m}^{-3}$ ); the plant area index (PAI) is 2 and the canopy height (h) is 18 m. Such a profile is typical of, for example, Maritime pine (Pinus pinaster) and Loblolly pine (Pinus taeda) stands. Finally, note that two simulations are performed for each canopy configuration, one with a parameterized fire and one without (referred to hereafter as “fire” and “no-fire” simulations).

## 190 3 Results and discussion

### 3.1 Analysis methodology

Perturbation wind components ( $u'$ ,  $v'$ ,  $w'$ ) and temperature ( $T'$ ) are computed by subtracting ~~30-min~~ 30-minute mean quantities from the no-fire simulation from the instantaneous values (output every second). Use of the no-fire mean ensures that modification of the mean variables by the fire does not influence the calculation of perturbations. Instantaneous TKE is subsequently computed as  $\frac{1}{2} (u'^2 + v'^2 + w'^2)$  and turbulent heat fluxes are computed as  $u'T'$  (horizontal) and  $w'T'$  (vertical). In this study, spatiotemporal mean quantities in a layer of depth  $3 \cdot h$  are examined first (Section 3.2), followed by analysis of instantaneous variables inside the canopy layer (Section 3.3). For the mean variable analysis (Section 3.2), turbulent and mean quantities are averaged along the y-axis and over the ~~30-min~~ 30-minute period during which the fire is applied. Subsequently, vertical (x-z) cross sections of the difference between the fire and no-fire mean quantity (hereafter, the fire anomaly) are displayed along with the corresponding no-fire mean quantity. For the instantaneous variable analysis (Section 3.3), box and whisker plots of instantaneous variables within the canopy layer are compared between the three zones (**Upstream**, **Center**, and **Downstream**) for each case (NG, CG,

205 UG, and DG). Note that in all box and whisker plots, outliers are determined using an interquartile range test: points are considered outliers if they are larger than  $q_3 + w(q_3 - q_1)$  or smaller than  $q_1 - w(q_3 - q_1)$ , where  $w$  is the maximum whisker length (herein, 1.5), and  $q_3$  and  $q_1$  are the 75th and 25th percentiles, respectively. This value of  $w$  corresponds to approximately  $\pm 2.7\sigma$  and 99.3% coverage if the data are normally distributed, where  $\sigma$  is the standard deviation.

## 210 3.2 Mean variable analysis

Examination of the four cases begins with vertical cross-sections of the spatiotemporal mean u-component of the wind (Fig. 2); see Section 2.3.3.1 for a description of the averaging procedure. Consider the no-fire wind field in the absence of fire first (contour lines). In the no gap case (Fig. 2a), one finds a weak wind regime within the canopy and a layer of pronounced vertical wind shear centered near the top of the canopy (green line). Introduction of the gap (Figs. 2b-d) yields a near-surface wind reversal within the gap (i.e., recirculation zone) and a tongue of stronger winds penetrating from above the canopy into the gap. Such a wind flow pattern is consistent with flux tower observations and LES modeling of flow through a 60 m wide gap as reported in Schlegel et al. (2012) and Queck et al. (2015). With the fire implemented (color shading), a broadly similar pattern in the fire anomaly field is seen in all four cases: positive anomalies centered on the fire, and negative anomalies mainly 100-200 m downstream of the fire center. The magnitude of the anomaly is sensitive to the position of the gap relative to the fire: the largest fire anomaly occurs in the case where the fire zone is co-located with the recirculation zone (case CG) and the weakest fire anomaly occurs in the case where the fire zone is co-located with the transition zone downstream of the gap where the westerly flow through the canopy in the absence of fire is stronger than corresponding flow through a homogeneous canopy (case UG).

Proceeding to vertical cross-sections of vertical wind velocity (Fig. 3), a weak and nebulous field of vertical motion is evident above the uniform canopy (case NG) in the absence of fire (Figs. 3a). In the continued absence of any fire, introduction of the gap (Figs. 3b-d) yields a vertical motion field (contour lines) consisting of a compact updraft on the upwind (i.e., west) side of the gap (solid lines) and a broad downdraft on the downwind (i.e., east) side of the gap (dashed lines). The vertical velocity couplet completes a clockwise circulation within the gap (cf. Figs. 2,3) that has been documented in previous studies (Schlegel et al., 2012; Queck et al., 2015). Small differences in the magnitude of the circulation between gap cases is likely evidence of the impact of transient disturbances in the unstable boundary layer on flow within the gap (not shown). Introduction of the fire yields a fire anomaly couplet of broader scale than the vertical velocity couplet associated with the gap itself, consisting of a negative (positive) fire anomaly on the upwind (downwind) side of the fire. Notably, the positive fire anomaly appears to be less sensitive to the position of the gap relative to the fire than the negative anomaly, which is weakest in case UG and strongest in case CG. Note that the small difference in positive fire anomaly between cases is not the result of spatial averaging in the

y-direction, as determined by an examination of horizontal cross-sections of the fire anomaly (not shown). The strongest negative anomaly occurs in the case wherein the upwind side of the fire (and fire-induced downdraft) coincides with the upwind side of the gap (and associated updraft), i.e., in case CG.

245 Examining total (resolved plus ~~SGS~~sub-grid scale) TKE in the absence of fire or gap (Fig. 4a, contours), a three-layer structure is seen, with an above-canopy maximum between 30 and 40 m AGL, a secondary in-canopy maximum at the surface, and a minimum in the upper canopy. Introduction of the gap induces a largely homogeneous TKE field within the gap and a TKE maximum above the gap, with a tongue of higher TKE penetrating into the clearing from above; the influence of the  
250 gap on the TKE spatial structure diminishes rapidly with downstream distance from the clearing. As with the horizontal and vertical velocity fields, the TKE pattern inside and out of the gap is consistent with the LES study of Schlegel et al. (2012) (their Fig. 10a; case HOM). With the fire heat source engaged (color shading), a fire anomaly maximum develops over or immediately downstream of the fire center. The largest fire anomaly occurs in case CG and the weakest anomaly occurs in case  
255 UG, mirroring the fire anomaly pattern for the u-component of the wind (Fig. 2). Analysis of the resolved TKE budget (not shown) indicates that buoyancy production is the primary source of the near-surface TKE anomaly.

With analysis of mean wind and TKE complete, some brief discussion of potential interactions between the gap-induced and fire-induced circulations, and the possible influence of the circulations on turbulence above the fire, is in order. As evidence of such interactions is difficult to assess from difference fields of 30-minute mean fire- and no-fire simulation wind components, vertical cross-sections of 1-minute mean wind components from the fire and no-fire simulations have also been examined (not shown). For most of the 30-minute period that the fire heat source is applied, there is no evidence of the gap-induced circulation. However, there are brief intervals when the gap  
260 circulation is more dominant, including the minute after the fire is switched on and sporadically throughout the 30-minute period. Thus, on short timescales (e.g., 1-2 minutes), TKE and wind gusts are potentially influenced by the gap circulation, but over longer timescales (e.g., 30 minutes), the influence of the gap circulation is likely minimal.

Proceeding to temperature in the absence of fire or gap (Fig. 5a), a superadiabatic lapse rate  
270 is evident ( $\sim 3.75 \text{ K } 100 \text{ m}^{-1}$ ), along with a weak horizontal gradient of negative sign, related to transient features in the unstable boundary layer (not shown). With the gap introduced, a pronounced horizontal gradient develops across the gap, with the axis of coolest temperatures just downstream of the gap. The influence of the gap on the magnitude of the fire anomaly is more modest than with the other variables, with only ~~about a~~ 1.1 K (about 4%) difference in anomaly magnitude between  
275 the cases with the largest (CG) and smallest (UG) anomalies. However, the downstream limit of the anomaly zone is sensitive to gap position, with anomalies extending farthest downstream in case UG. Differences in the downstream extension of temperature anomalies are attributable to differences in

the magnitude of temperature advection downstream of the fire, a claim that is supported by a close examination of the u-component of the wind in each case (Fig 2b).

280 As this is a study of fire-atmosphere interactions in heterogeneous forests, a relevant question to ask is what role, if any, do gaps play in vertical heat transport? In other words, do gaps act as vents for hot gases? To help answer this question, we examine vertical (horizontal) turbulent mixing as represented by the vertical (horizontal) gradient of vertical (horizontal) turbulent heat flux, in a vertical cross section (Figs. 6 and 7). The pattern of vertical and horizontal turbulent mixing anomaly  
285 is the same in all cases: in the vertical, heat is mixed upward away from the surface heat source, and in the horizontal, heat is mixed in the downstream direction. As was the case for the other variables examined (e.g., u-component of the wind, vertical velocity), the strongest and weakest anomalies occur in cases CG and UG, respectively. In other words, the strongest turbulent mixing occurs when the gap is positioned above the fireline, and the weakest turbulent mixing occurs when the gap  
290 is positioned upstream of the fireline. These results indicate that gaps in forest canopies have the potential to play a ~~substantial~~ role in the vertical as well as horizontal transport of heat away from the fire.

Before concluding this section, some discussion of possible advantages and disadvantages of the idealized modeling framework used in this study is in order. The fire is represented herein as a static  
295 line of enhanced surface vertical turbulent heat flux that is independent of both temporal and spatial variability in the atmosphere and the presence or absence of vegetation in its vicinity. Unlike coupled fire-atmosphere models such as FIRETEC and WRF-Fire (Coen et al., 2013), ARPS-CANOPY has no fire spread module; thus, the complex interactions between fire, fuels, and atmosphere simulated in models like FIRETEC are only partially accounted for in ARPS-CANOPY. The absence of a fire  
300 spread module eliminates complexity as well as uncertainty related to fire spread routines, however, it also raises concerns regarding the applicability of results to real-world fires. For example, the relationship of fire anomaly magnitude to gap position identified in this study is complicated by the fact that fire intensity may weaken as the fireline moves into a gap, as shown in Pimont et al. (2011) using FIRETEC. The reader is advised to keep the advantages and limitations of the idealized modeling  
305 framework in mind when interpreting the results of this study.

### 3.3 Instantaneous variable analysis

Acknowledging that fire-atmosphere interactions occur on a variety of temporal and spatial scales, we proceed from analysis of time and space-averaged quantities to analysis of instantaneous variables inside the canopy in the presence of fire. The analysis begins with the instantaneous u-component  
310 of the wind (Fig. 8) in case NG (Fig. 8a). In zone U, upstream of the fire, the u-component inside the canopy is in the range  $-1.88$  to  $2.67 \text{ ms}^{-1}$ , with a median value of  $0.48 \text{ ms}^{-1}$ . In zones C and D, over or downstream of the fire, the range of wind speeds is considerably larger [C:  $u \in (-3.08, 3.74)$ ; D:  $u \in (-3.09, 3.44)$ ] and the median is ~~about 40%~~  $0.2 \text{ ms}^{-1}$  larger than in zone U (~~about 40 % larger~~).

Thus, it appears that the fire has a pronounced effect on the magnitude of horizontal wind gusts as well as the intensity of the mean wind within the canopy. Examining cases UG, CG, and DG (Fig. 8b-d), it is evident that removal of vegetation from a zone increases both the width of the distribution and the median, especially when the gap is over or downstream of the fire (e.g., zone C in case CG, zone D in case DG). Wind speeds are larger wherever a gap is present due to reduced drag and turbulent dissipation. The finding of larger instantaneous wind speeds within gaps is consistent with the findings of Pimont et al. (2009, 2011) in which wind gusts were found to be notably stronger in fuel breaks than in the surrounding forest canopy.

We next proceed to instantaneous vertical velocity (Fig. 9). A quick examination of all cases and zones shows that magnitudes of instantaneous vertical velocity inside the canopy are generally between 1.5 and 3.75  $\text{ms}^{-1}$ , about an order of magnitude larger than the magnitude of mean vertical velocity seen in Fig. 3. It is worth noting, however, that even larger instantaneous vertical velocities are present above the canopy within the mixed layer [O(5-10  $\text{ms}^{-1}$ )] (not shown). Proceeding to case NG (Fig. 9), we find that unlike the quasi-normal distribution of the u-component of the wind (skewness = -0.23), there is a positively skewed distribution of vertical velocity in zone U (skewness = 0.865). Over and downstream of the fire (zones C and D), the width of the distribution increases as well as the skewness (skewness = 1.67 and 0.92 in zones C and D, respectively). As with the u-component of the wind, introduction of a gap in a particular zone increases the width of the distribution, especially when the gap is over or downstream of the fire. However, the effect of the gap on the median vertical velocity value is ambiguousinconsistent, as the median in some cases remains unchanged (e.g., compare zone C in cases NG and CG; Figs. 9a,c) and in others switches sign (e.g., compare zone D in cases NG and DG; Figs. 9a,d).

Examination of instantaneous TKE (Fig. 10) in case NG (Fig. 10a) reveals a median value of 0.25  $\text{m}^2\text{s}^{-2}$  in zone U, but outlier values as large as 6.92  $\text{m}^2\text{s}^{-2}$ . Over and downstream of the fire (zones C and D), the median is more than double the zone U value, and outlier values increase to as large as 8.81  $\text{m}^2\text{s}^{-2}$  in zone C. The introduction of forest gaps yields a considerably more turbulent atmosphere, as judged by median and outlier values. When the gap is centered on the fire, a median TKE of 0.91  $\text{m}^2\text{s}^{-2}$  is produced, with instantaneous values as large as 14.93  $\text{m}^2\text{s}^{-2}$ . Similar conditions occur when the gap is positioned downstream of the fire (case DG); note that the largest median value in any zone occurs in zone D in case DG (1.08  $\text{m}^2\text{s}^{-2}$ ). It is clear from this analysis that canopy gaps serve to locally increase turbulence in an otherwise drag-tempered environment. Furthermore, large TKE values may occur inside a gap in the forest canopy even though the gap is not directly above the fire.

Lastly, we examine instantaneous temperature (Fig. 11). Beginning with case NG (Fig. 11), the influence of the fire on temperature is evidenced by the nearly 27 K difference in maximum temperature between zones U (307.94 K) and C (334.79 K), as well as the 1.3 K difference in median temperature values between the two zones. Whereas this effect of the fire on temperature is expected,

the influence of the gap on temperature is, however, less intuitive. In contrast to the other variables examined (e.g., TKE), the instantaneous temperatures in a particular zone (as judged by the maximum and median values) either remain unchanged or actually decrease when a gap is introduced. The result that near-surface temperatures above a fire are less hot in the absence of vegetation, as compared to a homogeneous forest, is consistent with the findings of Kiefer et al. (2015). Recall that the same amount of heat is fluxed into the atmosphere per second per unit area ( $25 \text{ kWm}^{-2}$ ); introduction of the gap increases the intensity of turbulent mixing and serves to reduce the maximum temperature compared to uniform vegetation.

#### 4 Summary and conclusions

In this study, ARPS-CANOPY has been utilized to examine the sensitivity of fire-perturbed variables to the presence of gaps in forest cover, and to the position of such gaps relative to the fire line. A single plant area density profile was used to represent a canopy with a moderately dense overstory and sparse trunk space, and a  $25 \text{ kWm}^{-2}$  heat flux was applied within a 50-m wide fireline to represent a low-intensity fire. Simulations with and without the fire were performed to evaluate the role of forest gaps on the background as well as the fire-perturbed atmosphere. Acknowledging the broad range in timescales relevant to fire-atmosphere interactions, analysis of both mean and instantaneous variables was performed. A summary of the model results is presented in Fig. 12, based primarily on the mean variable analysis in Figs. 2-7.

In the absence of fire (Fig. 12; black arrows and grayscale shading), forest gaps were found to have a pronounced effect on mean wind and turbulence. Absent any gaps (Fig. 12a), the model exhibited weak wind speeds near the surface, strong vertical wind shear across the canopy-atmosphere interface, and two TKE maxima, a primary maximum above the canopy and a secondary maximum near the surface. Implementation of the gap (Figs. 12b-d) yielded a recirculation zone within the clearing, and a more homogeneous TKE field than in the surrounding forest. Downstream of the gap, mean wind speeds were stronger than flow through a homogeneous canopy, whereas the TKE field was similar in magnitude to the TKE field inside a homogeneous canopy.

In all cases, implementation of the fire (Fig. 12; colored arrows and shading) induced a positive (negative) vertical velocity anomaly downstream (upstream) of the fire, with a positive horizontal wind anomaly located immediately above the heat source (i.e., westerly inflow to the fire-induced updraft). Whereas the positive vertical velocity anomaly showed little sensitivity to gap position, the negative vertical velocity anomaly and horizontal wind anomaly were found to be strongest in case CG, and weakest in case UG. The differences in horizontal and vertical wind anomaly strength between cases were attributed to differences in background flow between the gap and the surrounding forest. Consistent with the mean wind anomalies, TKE and turbulent mixing anomalies were largest in case CG and weakest in case UG. Differences in TKE and turbulent mixing anomalies between

cases resulted not from differences in background flow but from differences in fire-induced buoyancy between the gap and the surrounding forest.

This study has provided insight into the sensitivity of ~~fire-atmosphere interactions~~ fire-induced perturbations to the presence of gaps in forest cover. The results presented herein suggest that in order to understand how the fire will alter wind and turbulence in a heterogeneous forest, one needs to first understand how the forest heterogeneity itself influences the wind and turbulence fields *sans* fire. Furthermore, caution is recommended when applying studies of fire-atmosphere interactions in homogeneous canopies to forests with gaps. However, given the limited number of experiments performed, and the generally modest differences in perturbations between cases, caution should be exercised when extrapolating results of this study to other fires.

Despite the progress documented herein, much work remains. Future efforts planned ~~includes~~ include implementing a moving fire through a forest gap, ~~and~~-exploring the sensitivity of fire-atmosphere interactions to canopy profile shape, and performing statistical significance testing with a larger suite of experiments, including experiments with higher-intensity fires.

#### 400 **Data availability**

The data for this paper are stored at the NCAR-Wyoming Supercomputing Center (NWSC). For data requests, please contact Dr. Michael Kiefer at mtkiefer@msu.edu.

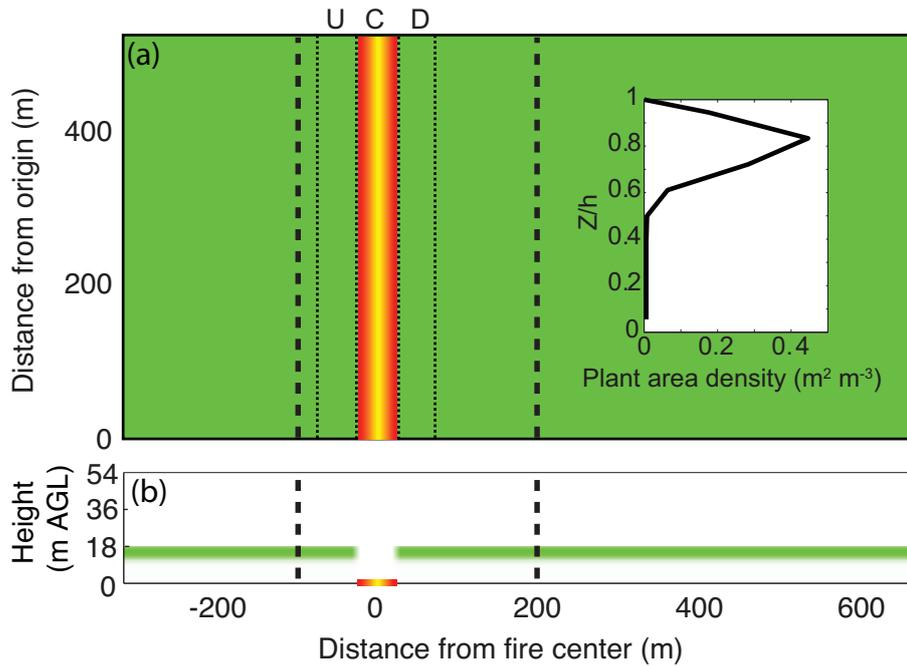
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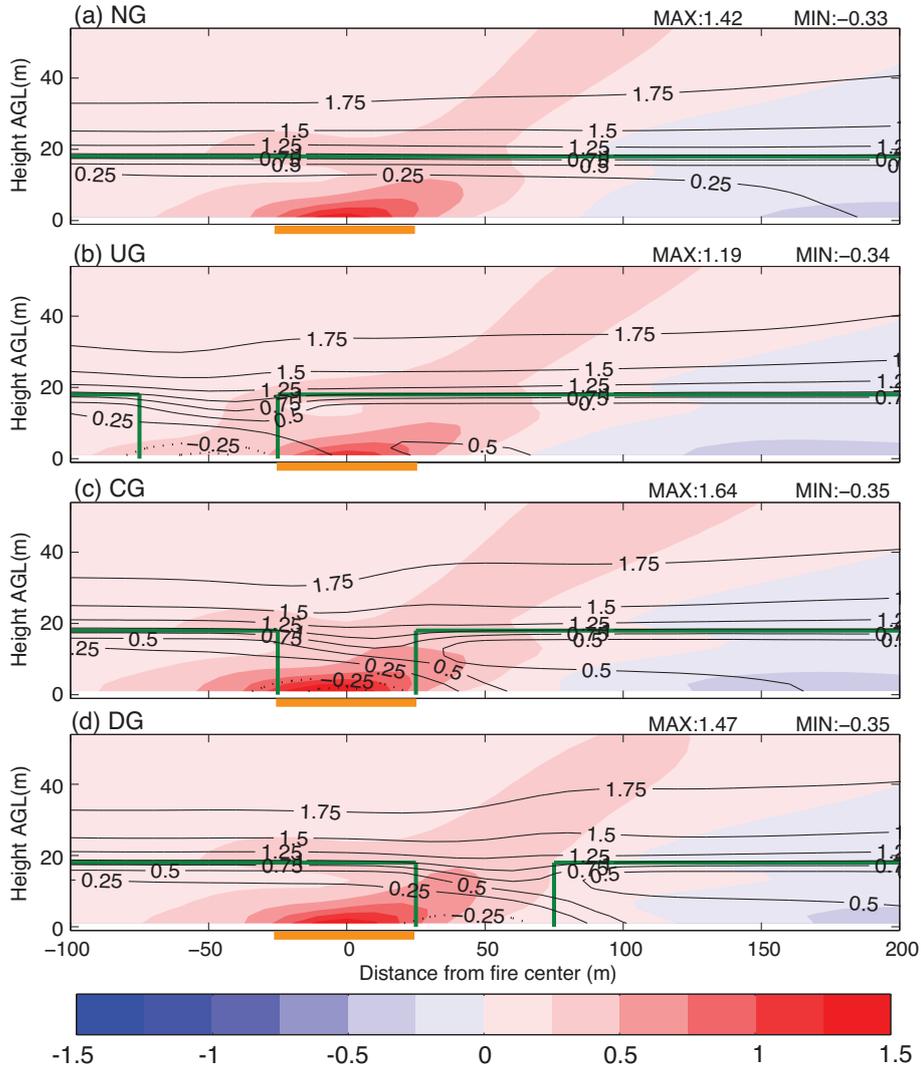
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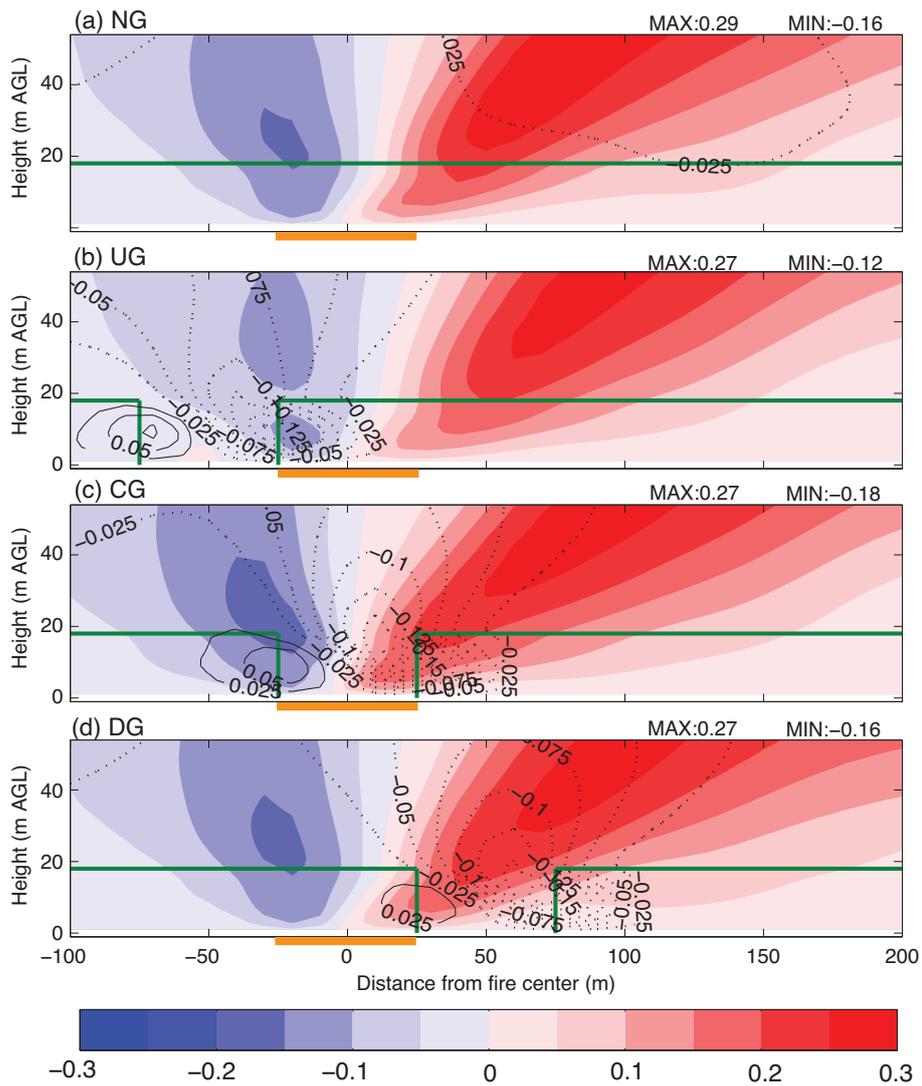
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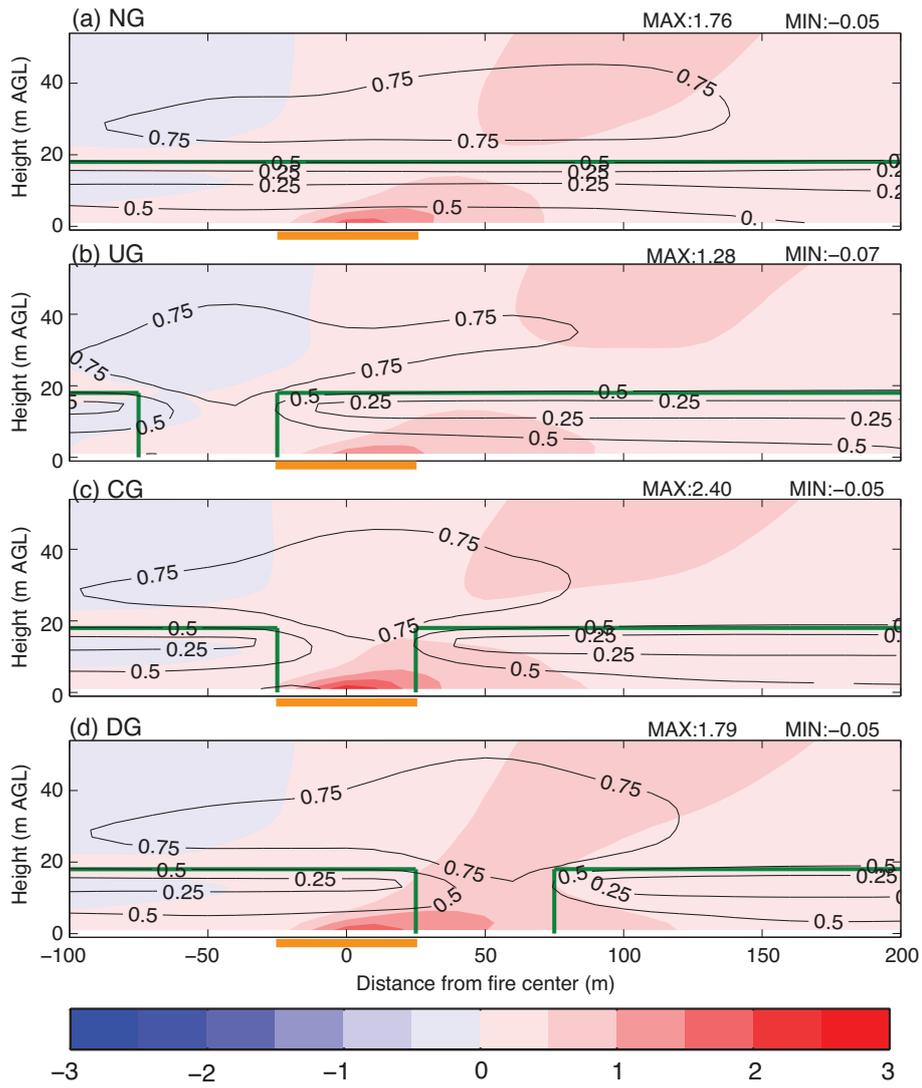
**Figure 1.** Experiment design summary, with (a) planview and (b) vertical cross-section depictions of canopy and fire. In panel (a), forest is depicted with green shading and surface heat flux in fire strip is shaded from red (weakest)  $\rightarrow$  yellow (strongest). Fire strip is divided into three zones, **U**pstream, **C**enter, and **D**ownstream, with three gap cases considered: gap in the upstream zone (UG), gap in the center zone (CG), and gap in the downstream zone (DG). Inset panel in (a) depicts the plant area density profile applied at all forested points; canopy height ( $h$ ) = 18 m. In panel (b), a vertical cross section of plant area density in the  $x$ - $z$  plane is provided for case CG, along with the location of the surface fire. Thick dashed lines denote the portion of the domain displayed in subsequent figures.



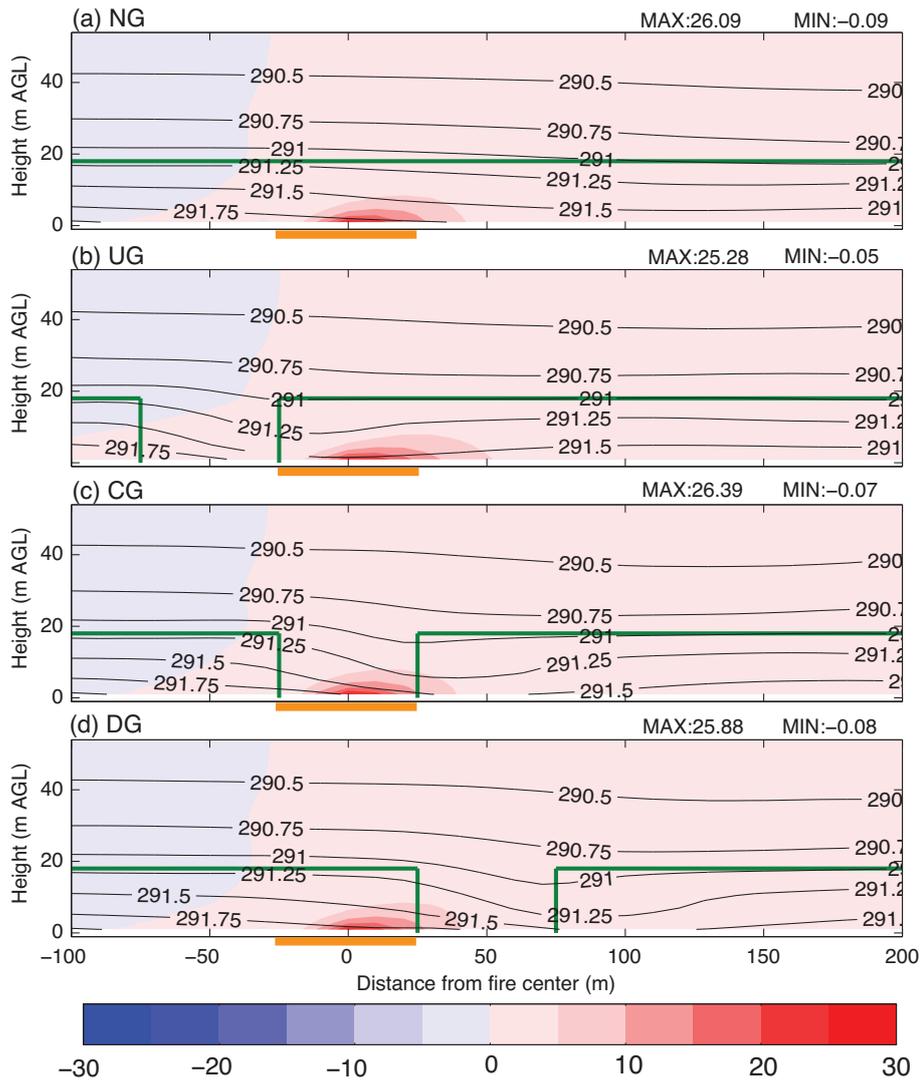
**Figure 2.** Vertical cross-sections of the u-component of the wind ( $\text{ms}^{-1}$ ), averaged in time (30-minute) and space (along-fireline); contours denote the no-fire case ( $0.25 \text{ ms}^{-1}$  interval), and shading depicts the difference between the fire- and no-fire cases ( $0.25 \text{ ms}^{-1}$  interval). The fire zone is denoted with an orange line, and the perimeter of the forest canopy is indicated with a green line. The maximum and minimum fire–no-fire difference for each case is included above each panel. Note that only a sub-set of the domain is displayed in each panel (100 m upstream to 200 m downstream of the fire center); see Fig. 1.



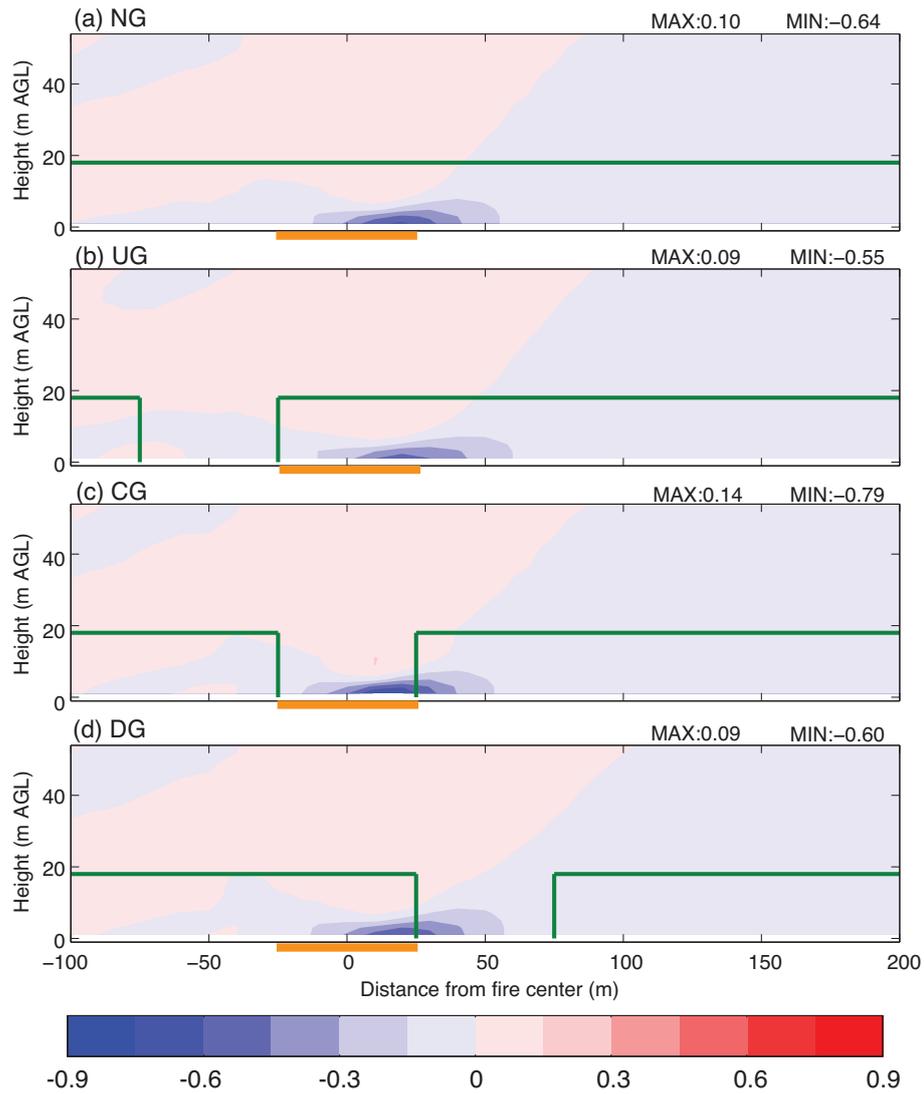
**Figure 3.** As in Fig. 2, but for vertical velocity ( $\text{ms}^{-1}$ ); contour interval is  $0.025 \text{ ms}^{-1}$  and shading interval is  $0.05 \text{ ms}^{-1}$ .



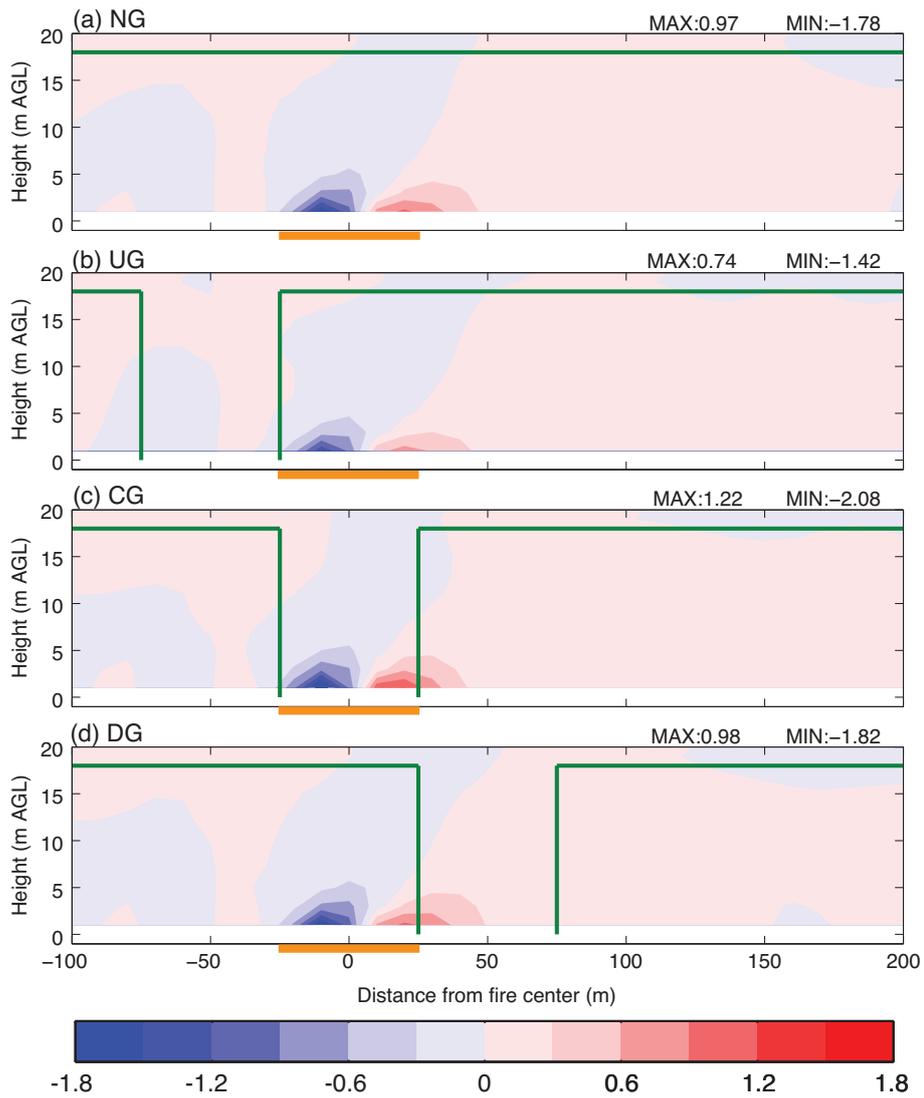
**Figure 4.** As in Fig. 2, but for TKE ( $\text{m}^2\text{s}^{-2}$ ); contour interval is  $0.25 \text{ m}^2\text{s}^{-2}$  and shading interval is  $0.5 \text{ m}^2\text{s}^{-2}$ .



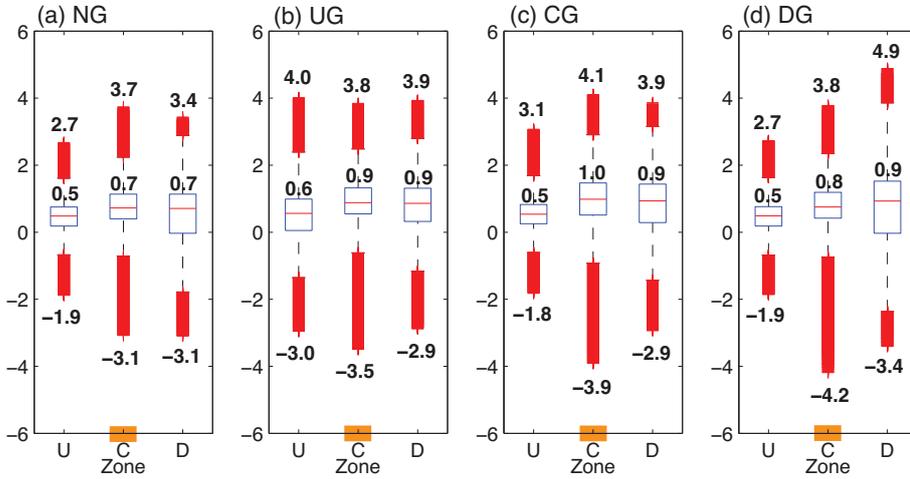
**Figure 5.** As in Fig. 2, but for temperature (K); contour interval is 0.25 K, and shading interval is 5 K.



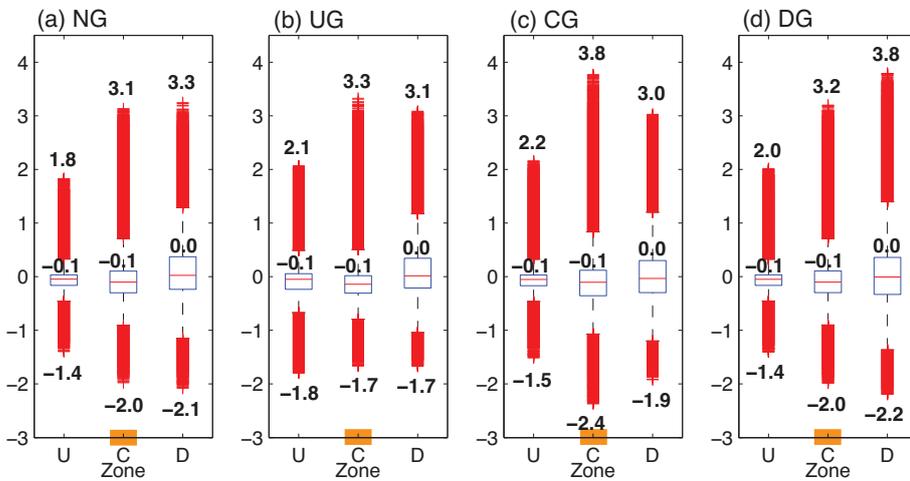
**Figure 6.** As in Fig. 2, but for the vertical gradient of the vertical turbulent heat flux ( $Ks^{-1}$ ); shading interval:  $0.15 Ks^{-1}$ . The no-fire case is omitted due to small values relative to fire case.



**Figure 7.** As in Fig. 2, but for the horizontal gradient of the horizontal turbulent heat flux ( $Ks^{-1}$ ); shading interval:  $0.3 Ks^{-1}$ . Note that the y-axis only extends up to 20 m AGL.



**Figure 8.** Box and whisker plots of instantaneous u-component of the wind ( $\text{ms}^{-1}$ ) within the canopy for case (a) NG, (b) UG, (c) CG, and (d) DG. From left to right in each panel, plots correspond to grid points in the upstream, center and downstream zones (see Fig. 1 and canopy outlines in Fig. 2b-d for illustration of zones); [fire location indicated by orange rectangle](#). For each box and whisker plot, the top and bottom of the box denotes the 75% ( $q_3$ ) and 25% ( $q_1$ ) percentiles, the horizontal red line denotes the median, the whiskers extend away from the box to the highest and lowest points not considered outliers, and the red bars extend outward from the whiskers to the maximum and minimum values. Note that ~~outliers are determined using an interquartile range test: points are considered outliers if they are larger than  $q_3 + w(q_3 - q_1)$  or smaller than  $q_1 - w(q_3 - q_1)$ , where  $w$  is the maximum whisker length (herein, 1.5).~~ The median, maximum, and minimum values are labeled for each plot.



**Figure 9.** As in Fig. 8, but for vertical velocity ( $\text{ms}^{-1}$ ).

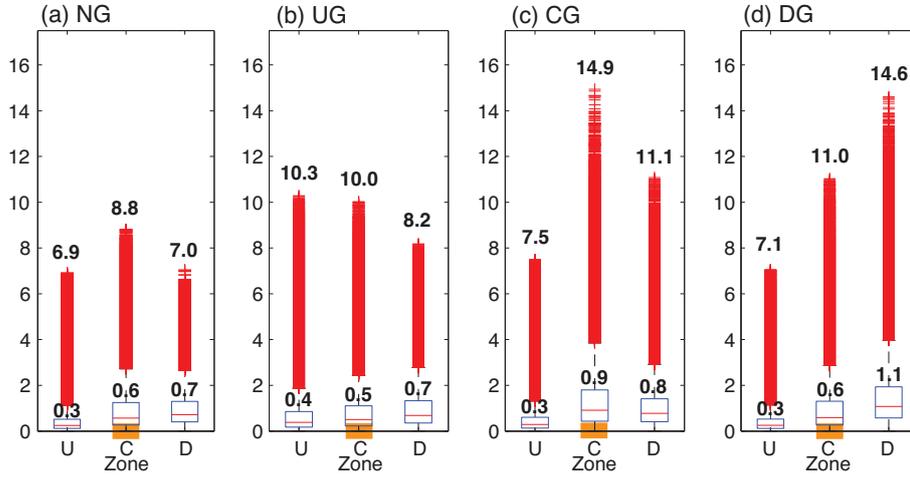


Figure 10. As in Fig. 8, but for TKE (m<sup>2</sup>s<sup>-2</sup>).

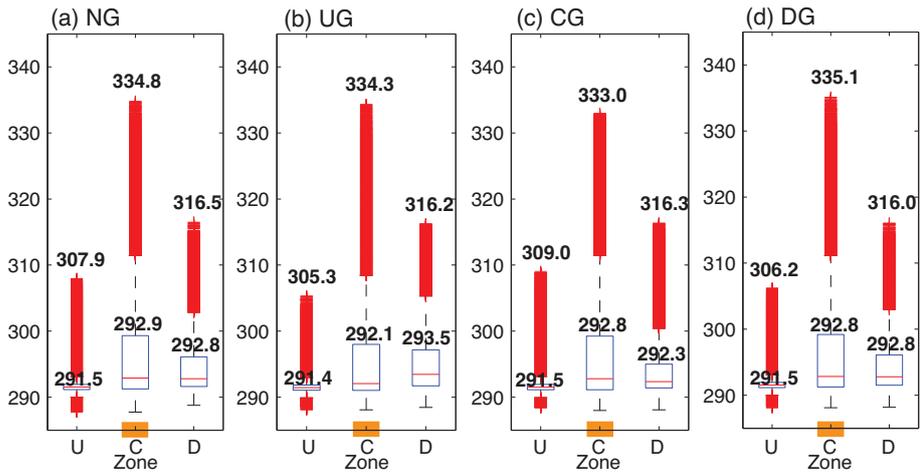
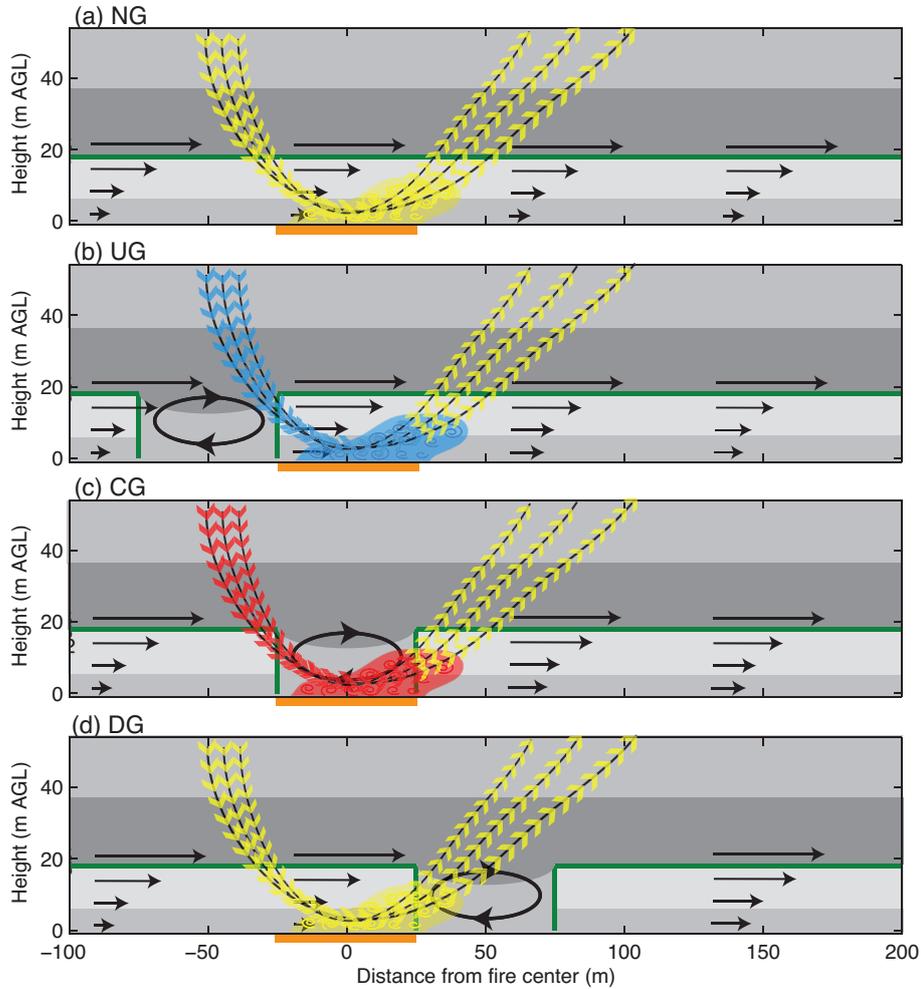


Figure 11. As in Fig. 8, but for temperature (K).



**Figure 12.** Conceptual model of fire-atmosphere interactions with different forest gap configurations. Background (i.e., no fire) state indicated with black arrows and grayscale shading: black horizontal arrows indicate the background mean u-component of the wind, black oval inside gap represents the gap recirculation zone, and shading indicates background mean TKE [light (weakest) → dark (strongest)]. Fire anomaly fields are depicted with colored arrows and shading: selected fireline-normal streamlines are indicated with colored arrows, and region of enhanced TKE and turbulent mixing of heat is represented by semi-transparent shading and embedded spirals. The magnitude of the fire anomaly is indicated by the color [blue (weakest) → yellow → red (strongest)]. As in Figs. 2-7, the fire zone is denoted with an orange line, and the perimeter of the forest canopy is indicated with a green line.