

All responses are in red.

General comments:

This study examined the impact of two disturbance sources including forest gaps and fire sensible heat on ambient atmosphere at small scales using a series of idealized numerical experiments. Technically, it's a well-organized paper with professional analyzing and writing skills. The structure is very clear with few typo or redundancy. However, the major issue with this manuscript is about its experiment design. In another words, the numerical experiments conducted here have limited capability to address the proposed scientific question that how could forest gaps influence the interactions between fire and atmosphere. The major difference between this study and previous ones (Linn et al., 2005, 2013; Pimont et al., 2009, 2011; Potter 2012) is that there is no feedback in fire behavior to induced atmosphere disturbance, not to mention that fire in this study is highly simplified as a line of enhanced surface sensible heat flux without any other burning processes. In this way the modeling results cannot be used directly to investigate the role of forest gaps in fire propagation, which is no doubt a very interesting topic with high scientific merits in forest management and fire protection. Under the current framework, we can only draw information about the interactive impacts from two independent disturbance sources as forest gaps and fire sensible heat on the near-surface meteorological properties. If this is what the authors intend to say (and they did make a clarification in the introduction that their focus is "on fire-atmosphere interactions in general"), then the current title of the manuscript is somewhat misleading.

First, we wish to make it clear that we do not claim in the paper that the results of this study can be applied directly to the study of fire propagation. In fact, on line 84-85, we state that our focus is "...not the specific impacts of gaps on fire behavior". We have edited two of the sentences in the penultimate paragraph of the *Introduction* section 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).”

To be consistent, we have also edited one sentence near the end of the *Summary and Conclusions* section as follows:

OLD:

“This study has provided insight into the sensitivity of fire-atmosphere interactions to the presence of gaps in forest cover.”

NEW:

“This study has provided insight into the sensitivity of fire-induced perturbations to the presence of gaps in forest cover.”

Another issue with the current modeling experiments is that the differences among each sensitivity simulations are too subtle to draw definitive conclusions. Such limited sensitivity could also be a consequence of low-intensity fire perturbations in experiment design. It’s suggested that an ensemble modeling experiment with high-intensity perturbations and statistical significance tests would be more convincing to evaluate the sensitivity of atmospheric responses to the two disturbances.

First, it is worth noting that the current version of ARPS-CANOPY is a predictive tool primarily developed for low-intensity fire applications (and other non-fire applications too). The prediction of local smoke dispersion from low-intensity fires is made challenging by the influence of a number of interrelated factors, including near-surface meteorological conditions, local topography, vegetation structure, and atmospheric turbulence within and above vegetation layers.

This study specifically focuses on the influence of gaps in forest canopies on atmospheric perturbations induced by low-intensity fires. This is highly relevant for understanding local plume behavior and smoke dispersion during prescribed low-intensity fires used for managing surface fuels in forested environments. We have modified the penultimate paragraph of the *Introduction* section to state that ARPS-CANOPY was primarily developed for use with low-intensity fires, wherein transport and dispersion of smoke are especially sensitive to local vegetation, and that in this study we are examining the impact of gaps in forest cover on atmospheric perturbations above *low-intensity* fires.

That said, we agree that performing a suite of experiments with both high and low intensity fires, and calculating the statistical significance of differences between experiments, is a worthwhile endeavor. However, there are two impediments to consider. First, the simulations are computationally expensive, as is the post-processing. To do statistical significance testing will require many more experiments, and thus a heavy computational workload. Second, great uncertainty exists regarding the application of a high-intensity fire in ARPS (e.g., accuracy of computations). In short, expanding the suite of cases to include high intensity fires and to

perform significance testing is not a trivial matter. We will address this matter in future work. The final sentence of the paper has been modified as follows:

OLD:

“Future efforts planned includes implementing a moving fire through a forest gap, and exploring the sensitivity of fire-atmosphere interactions to canopy profile shape.”

NEW:

“Future efforts planned include implementing a moving fire through a forest gap, 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.”

We have also added a cautionary statement near the end of the *Summary and Conclusions* section about drawing conclusions from a limited number of experiments, with limited sensitivity. Lastly, we removed the qualifier “substantial” when referring to the potential role that gaps may play in heat transport away from the fire.

Overall, I recommend major revisions with additional ensemble modeling experiments before a potential publication on the ACP journal. More detailed comments are specified as follows.

Specific comments:

(1) Model description:

In section 2.1, the authors introduce multiple modifications in the model to suit the numerical experiments. These modifications include adding the drag force, the enhancement of turbulence dissipation, and radiation interception due to the canopy, etc.

But no information is provided about changes in surface latent heat flux in the heterogeneous canopy due to evapotranspiration variability. In line 117, a constant albedo for forested areas is utilized. How about the albedo in these gap areas without the canopy coverage?

No explicit changes were made in the development of ARPS-CANOPY to account for the impact of the overlying canopy on surface evapotranspiration; however, surface evapotranspiration is impacted by the canopy indirectly, through shading of the surface and reduction of the wind speed due to canopy drag. For these idealized experiments, the albedo is set to 0.3 in the gaps. A description of this modification has been added to the text.

(2) Experiment design:

In line 158, a low-intensity fire strip is represented as a 25 kWm^{-2} surface static sensible heat flux within a 50-m wide north-south strip. How about the length and duration

of this fire strip? Previous studies (Scott and Reinhardt, 2001; Rogers, et al., 2015) have identified the distinct characteristics of low-intensity surface fire and high-intensity crown fire as well as their different impacts on the ecosystem and climate. Though the scale is different in this study, it would be still interesting to see differences of the two types of fire from a small-scale perspective.

The fireline is 500 m in length (the fire is only located in the child domain, which has a Y-dimension of 500 m). The fire is applied for a 30-min period. The missing details have been added to the text.

Regarding performing additional simulations with high intensity fires, please see our response to your General Comments (comment beginning “Another issue with the current modeling experiments...”).

(3) Simulation results:

In section 3.2, examination of different mean variables ends up with the same conclusion that the strongest fire anomaly occurs in the CG case and the weakest occurs in the UG case. However, this conclusion is based on the static fire assumption that fire itself has no response to ambient atmosphere disturbance. Would this conclusion be robust if we consider a more realistic fire with dynamic propagation? In the real world, fire reacts to local meteorological disturbances as well as changed fuel supplies in forest gaps with variable burning intensity, which may further interacts with ambient atmosphere in different ways like what we see here. In Pimont et al. (2011), their Fig. 5/7 demonstrates the variation of fire intensity along different forest zones. Such variability in fire intensity reaches the maximum in the Het0 case in their Fig. 7 that is similar with the forest gap setting in this study. It’s suggested to consider and discuss the potential limitations related to the idealized assumption before drawing the conclusion in the context.

We understand your concern about drawing conclusions from simulations performed with a one-way coupled model. We have added a paragraph to the end of Section 3.2 to discuss the limitations (and advantages) of the idealized modeling framework, to contrast the one-way coupled ARPS-CANOPY model with two-way coupled models such as FIRETEC and WRF-FIRE, and to caution the reader to keep the limitations (and advantages) of the idealized modeling framework in mind when interpreting results from this study.

Technical corrections:

(1) In line 197, it should refer to “Section 3.1” instead of “Section 2.3” for a description of the averaging procedure.

Corrected.

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-

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
30 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 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 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 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 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 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 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 σ 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 ms^{-1} , with a median value of 0.48 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 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 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 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 m^2s^{-2} in zone U, but outlier values as large as 6.92 m^2s^{-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 m^2s^{-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 m^2s^{-2} is produced, with instantaneous values as large as 14.93 m^2s^{-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 m^2s^{-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 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 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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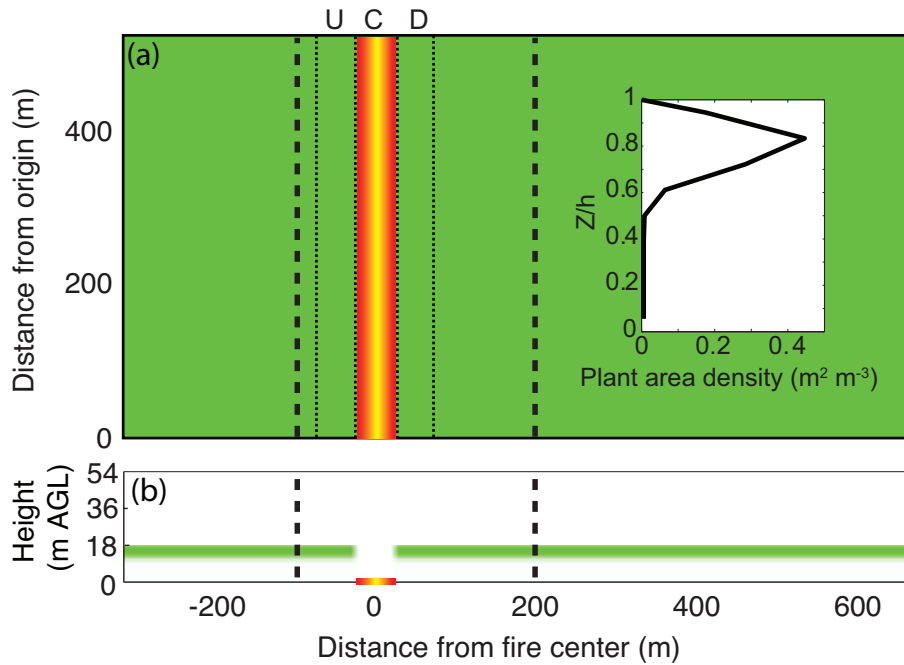


Figure 1. Experiment design summary, with (a) planview and (b) vertical cross-section depictions of canopy and fire. In panel (a), forest is depicted with green shading and surface heat flux in fire strip is shaded from red (weakest) → yellow (strongest). Fire strip is divided into three zones, **U**pstream, **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.

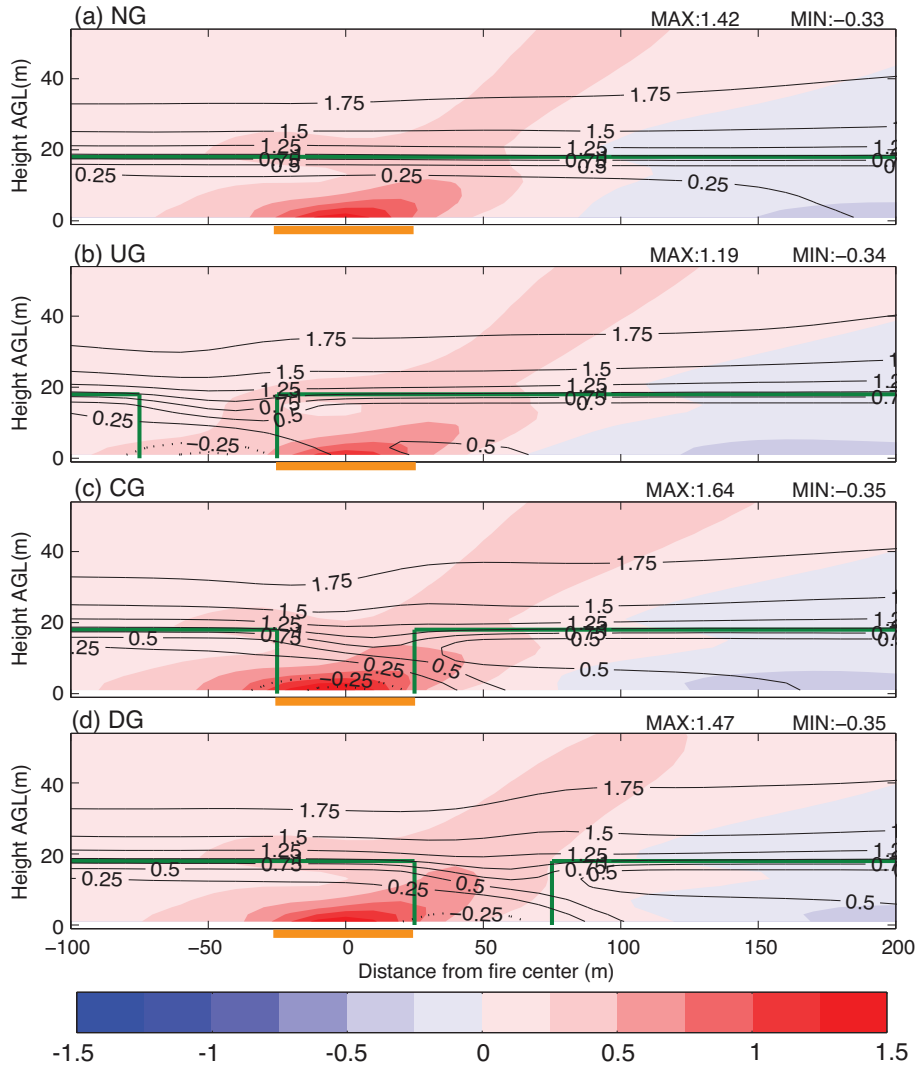


Figure 2. Vertical cross-sections of the u-component of the wind (ms^{-1}), averaged in time (30-minute) and space (along-fireline); contours denote the no-fire case (0.25 ms^{-1} interval), and shading depicts the difference between the fire- and no-fire cases (0.25 ms^{-1} interval). The fire zone 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.

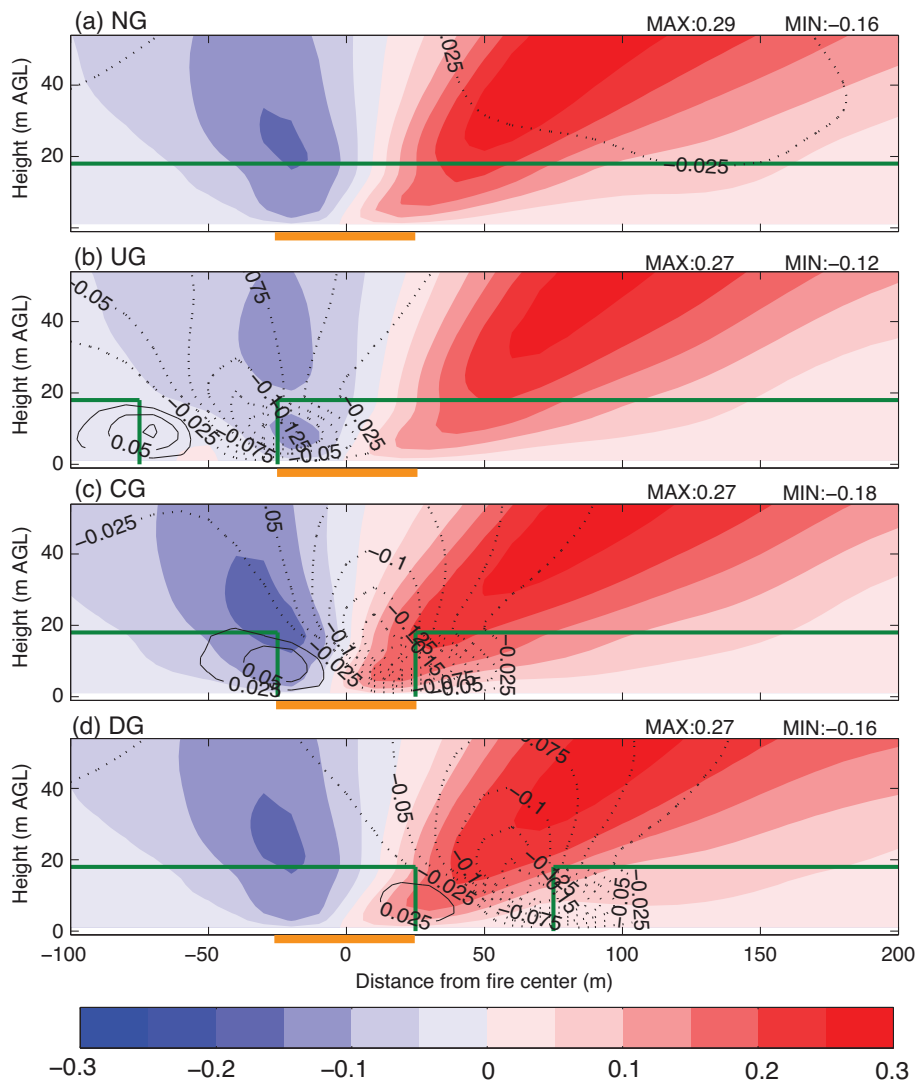


Figure 3. As in Fig. 2, but for vertical velocity (ms^{-1}); contour interval is 0.025 ms^{-1} and shading interval is 0.05 ms^{-1} .

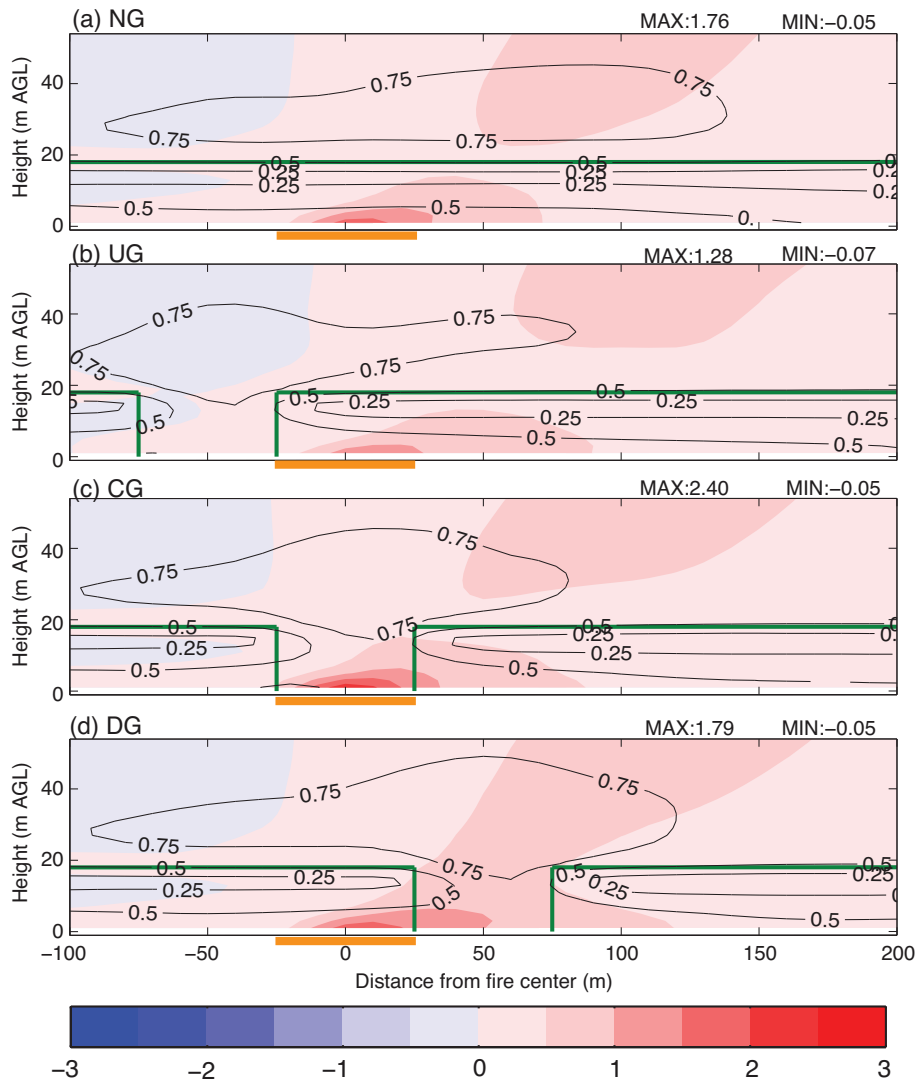


Figure 4. As in Fig. 2, but for TKE (m^2s^{-2}); contour interval is $0.25 \text{ m}^2\text{s}^{-2}$ and shading interval is $0.5 \text{ m}^2\text{s}^{-2}$.

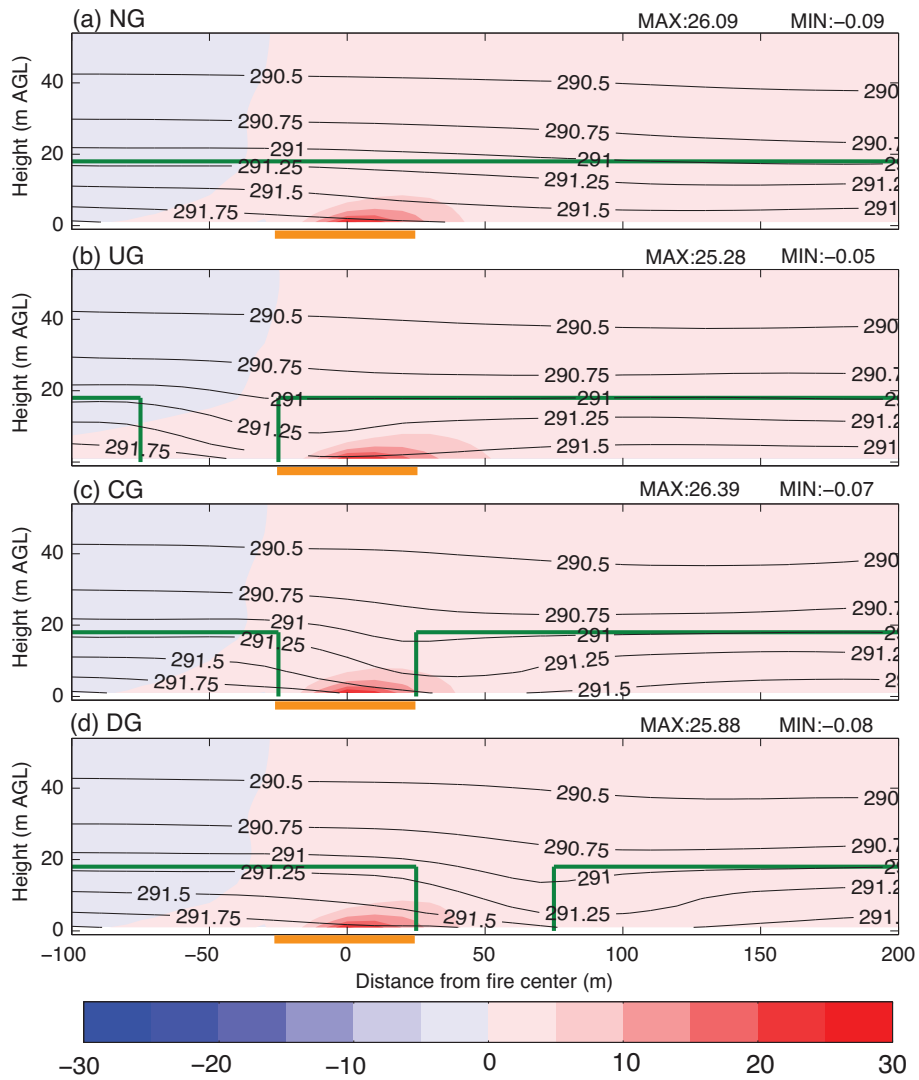


Figure 5. As in Fig. 2, but for temperature (K); contour interval is 0.25 K, and shading interval is 5 K.

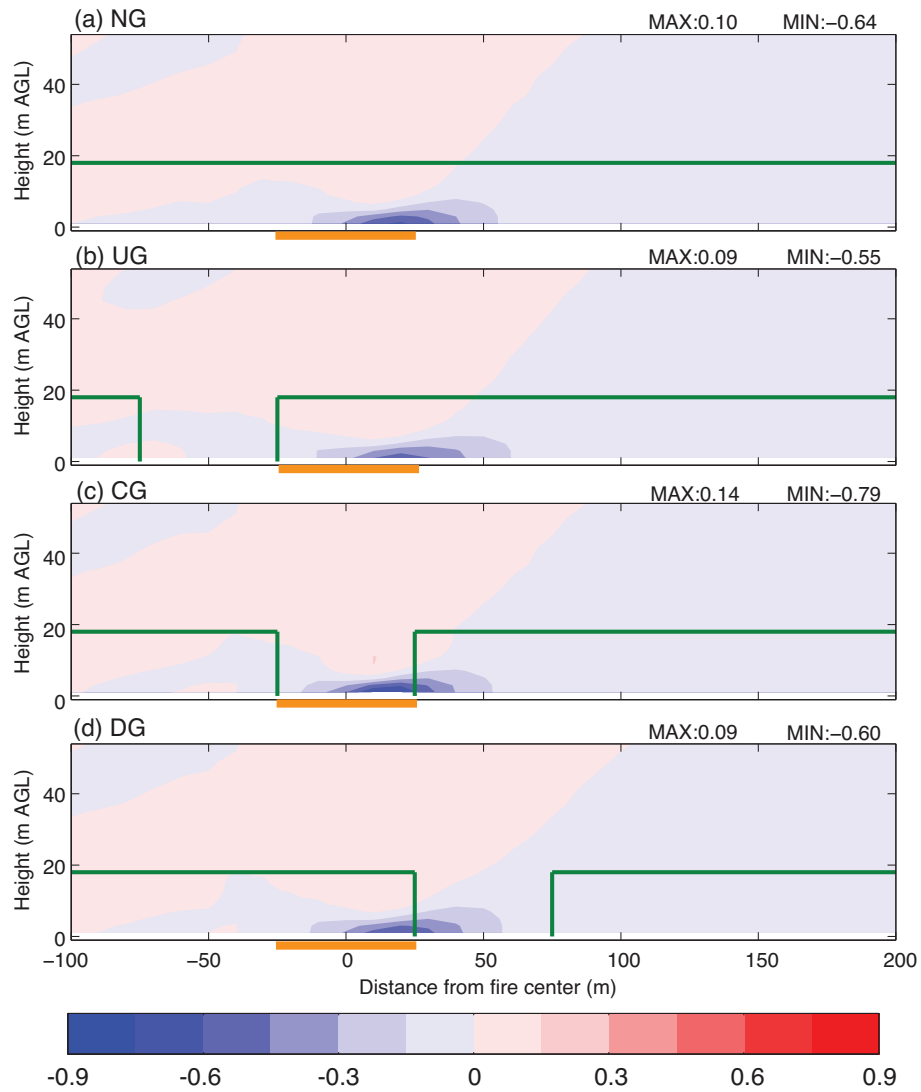


Figure 6. As in Fig. 2, but for the vertical gradient of the vertical turbulent heat flux (Ks^{-1}); shading interval: $0.15 Ks^{-1}$. The no-fire case is omitted due to small values relative to fire case.

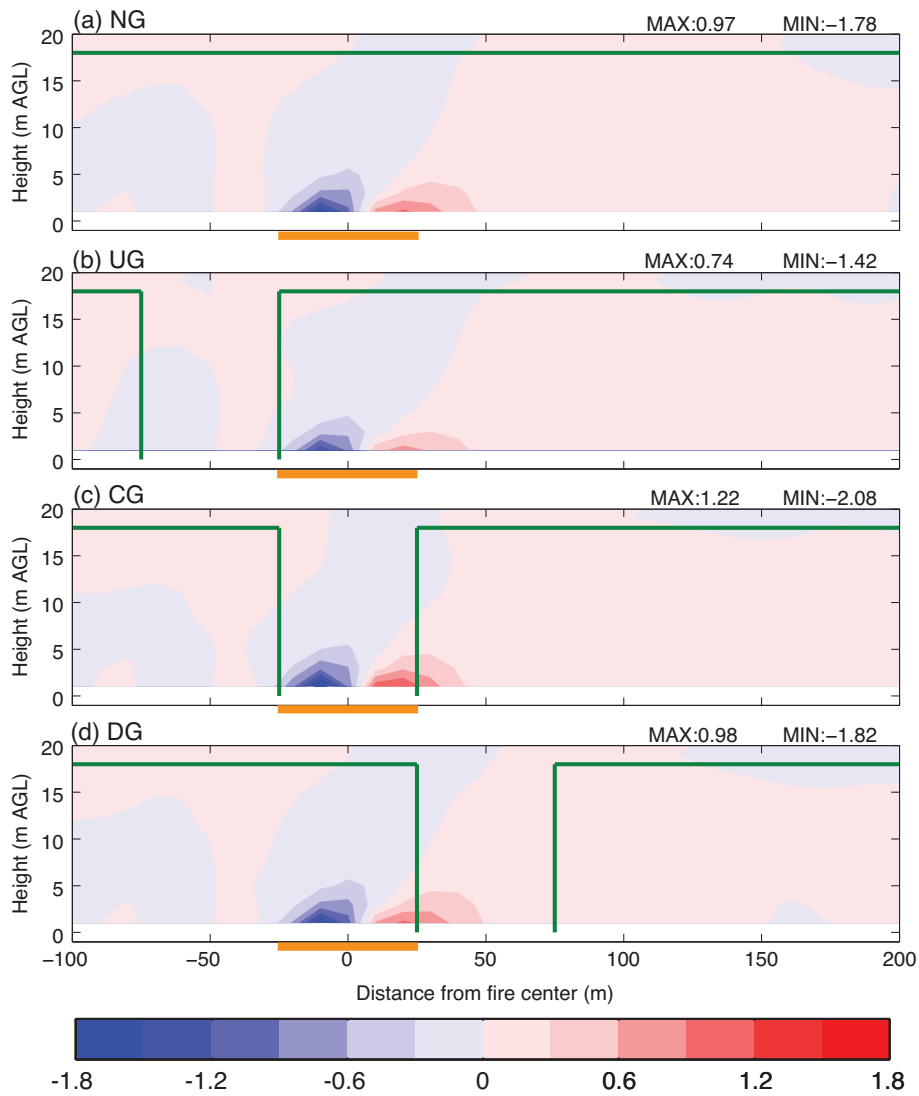


Figure 7. As in Fig. 2, but for the horizontal gradient of the horizontal turbulent heat flux (Ks^{-1}); shading interval: 0.3 Ks^{-1} . Note that the y-axis only extends up to 20 m AGL.

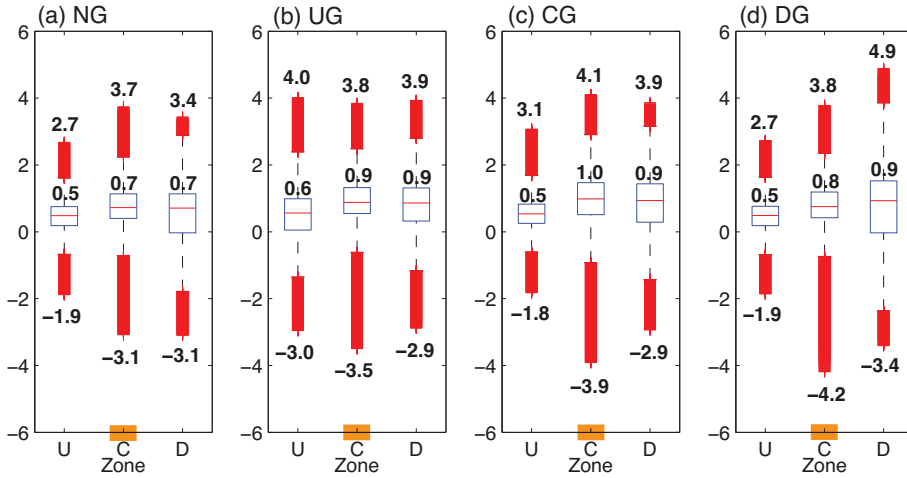


Figure 8. Box and whisker plots of instantaneous u-component of the wind (ms^{-1}) within the canopy for case (a) NG, (b) UG, (c) CG, and (d) DG. From left to right in each panel, plots correspond to grid points in the upstream, center and downstream zones (see Fig. 1 and canopy outlines in Fig. 2b-d 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.

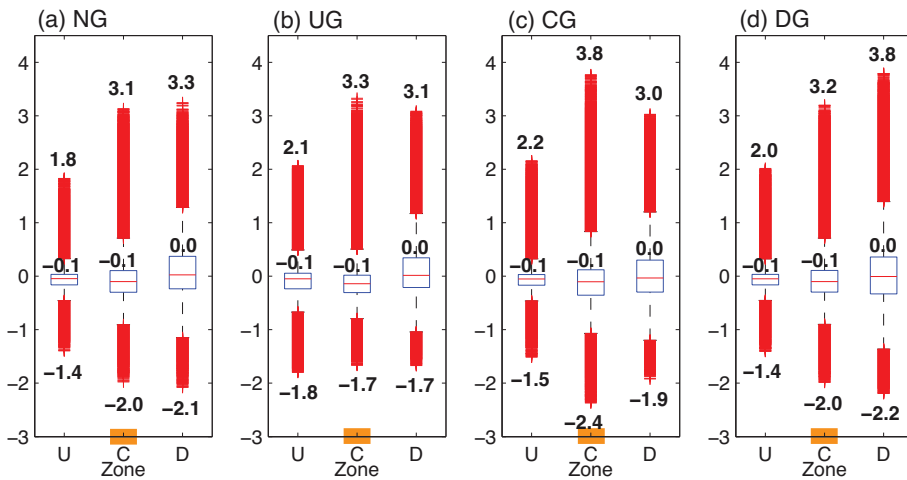


Figure 9. As in Fig. 8, but for vertical velocity (ms^{-1}).

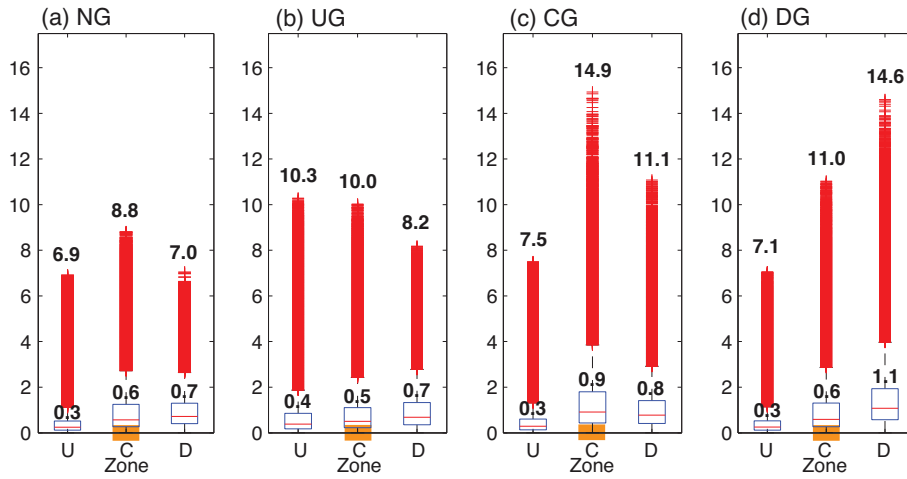


Figure 10. As in Fig. 8, but for TKE (m²s⁻²).

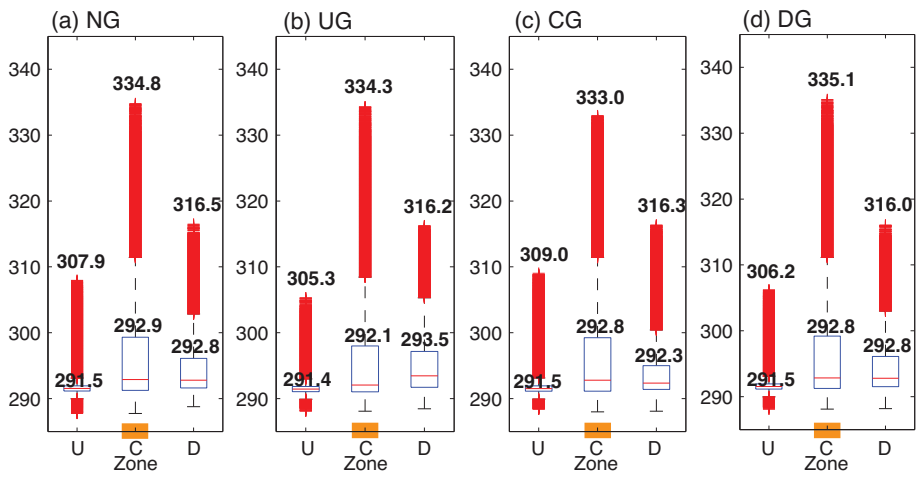


Figure 11. As in Fig. 8, but for temperature (K).

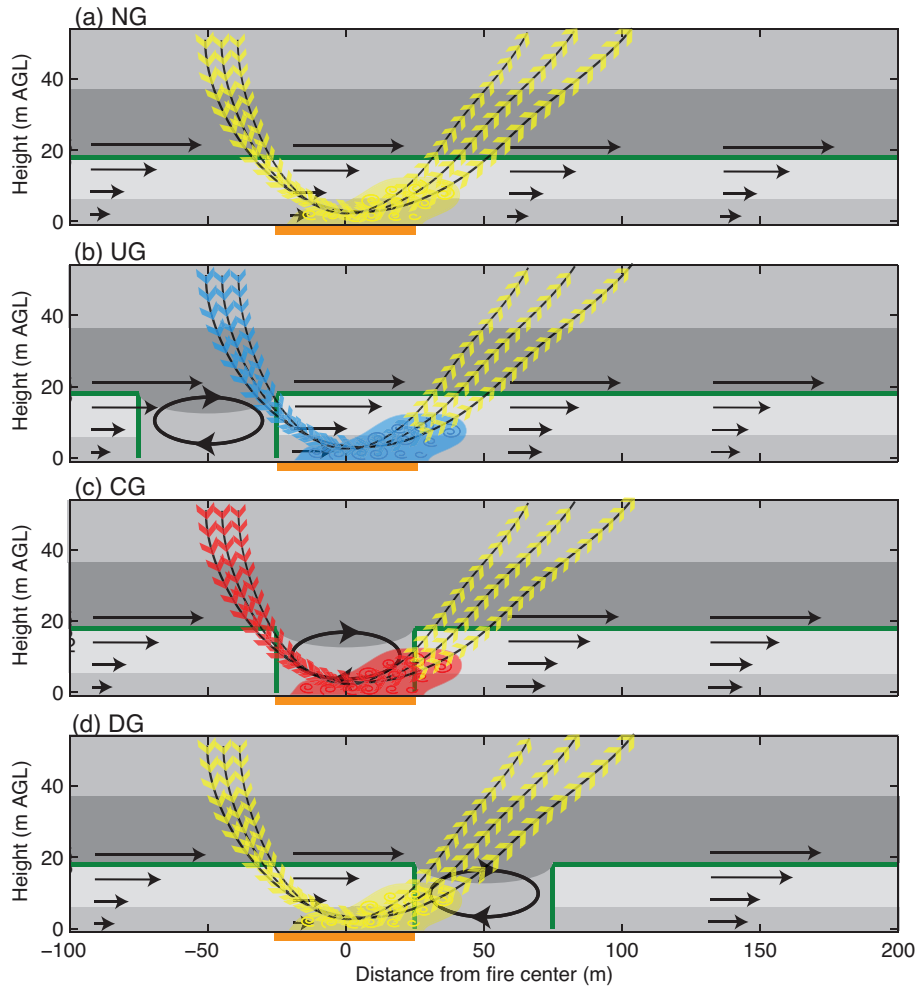


Figure 12. Conceptual model of fire-atmosphere interactions with different forest gap configurations. Background (i.e., no fire) state indicated with black arrows and grayscale shading: black horizontal arrows indicate the background mean u-component of the wind, black oval inside gap represents the 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.