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Perspective

Wildland fire entrainment: The missing link between wildland fire and its environment

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Abstract

Wildfires are growing in destructive power, and accurately predicting the spread and intensity of wildland fire is essential for managing ecological and societal impacts. No current operational models used for fire behavior prediction resolve critical fire-atmospheric coupling or nonlocal influences of the fire environment, rendering them inadequate in accounting for the range of wildland fire behavior scenarios under increasingly novel fuel and climate conditions. Here, we present a new perspective on a dominant fire-atmospheric feedback mechanism, which we term wildland fire entrainment (WFE). WFE is the fluid motion associated with air movement toward the fire driven by pressure gradients created by buoyant updrafts, and through integration of nonlocal influences on fire behavior, it plays a pivotal role in predicting wildland fire spread. WFE dynamically integrates all aspects of a fire's surrounding environment, fuels, topography, winds and fire line geometry to rate and pattern of fire spread and energy release. Because WFE explicitly incorporates fire-induced buoyancy, it links recent advances in idealized combustion research to the dynamic and highly variable wildland fire environment. Incorporating WFE into emerging fire models will allow more robust predictions of fire behavior and spread.

Keywords: fire behavior, fluid dynamics, wildfire, prescribed fire, coupled fire-atmosphere feedbacks

Introduction

Wildfires are increasingly destructive and projected to become worse with climate change (1). Scientists and managers must dramatically increase more proactive approaches to mitigate the catastrophic wildfire risk and increase the ecosystem resilience (2). Expanding these proactive management activities requires accurately anticipating fire behavior under increasingly novel climates and fire environment conditions than is currently possible (3), and wildland fire science has missed fundamental processes driving fire behavior (4). Current operational models cannot capture complex fire-atmosphere interactions (5, 6), which determine the influences of fire geometry and vegetation structure. This limitation also impacts the capacity of some of these models to effectively predict fire behavior under both novel climate and ecosystem conditions. A new paradigm in the approach, understanding, and representation of the fire-environment interactions that control fire behavior of wildfires is required to advance our prediction capabilities, particularly in the context of proactive management measures including mechanical and prescribed fire fuel hazard reduction treatments.

Wildland fire behavior is driven by the complex interactions of fire with its heterogeneous surroundings. These interactions are best explained by fluid dynamics and heat transfer processes that couple combustion with the local and nonlocal environment, capturing the nonlinear and potentially chaotic mechanisms controlling fire spread (7–9). However, current operational fire behavior models are built on a flawed conceptual foundation that fire spread can be predicted solely as a function of purely local conditions (i.e. fuel loading and moisture, wind speed, and slope). This assumption, which originated to avoid formulation complexity or computational expense, ignores connections between fire and the nonlocal conditions, which are beyond the immediate combustion zone of a fire (10). The influence of the fire environment on fire behavior is nonlocal, as fire is impacted by aspects of the fire environment at some distance away (i.e. fire behavior at a location cannot be reliably predicted by only considering the conditions at that point, but instead must account for the surrounding patterns and events as well). While there is increasing evidence that nonlocal factors like variations in the fire environment strongly influence fire behavior (9, 11), current wildland fire behavior models have no mechanism to account for the underlying 2-way fire-atmosphere feedback linking local and nonlocal conditions that influence the spread and evolution of wildland fires.

Here, we introduce the concept of wildland fire entrainment (WFE), which is distinct from plume entrainment or shear-induced entrainment, as a fundamental underpinning of fire behavior that mechanistically accounts for fire behavior dependencies on local

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and nonlocal variation in the fire environment. WFE accounts for these dominant fire-atmosphere feedbacks, and we believe that it is essential to building robust fire behavior predictions in many wildland fire scenarios. WFE is derived from fluid dynamics and represents the process that governs the near-surface atmospheric flow patterns that are drawn toward the vertically accelerating base of a buoyancy-induced rising column. WFE is distinguished from shear-induced entrainment, which is also prevalent in fire environments. WFE-induced flow patterns reflect a fire's spatial context including heterogeneities in the vegetation, slope, micrometeorological conditions, and other ignitions in regions surrounding a fire. As a primary means by which nonlocal aspects of the fire environment affect fire behavior, accounting for WFE allows for prediction of fire activity at one location as an integrated outcome of the heterogeneous fire environment. When incorporated into fire behavior modeling, WFE will enable improvements and understanding of when these nonlocal dependencies must be resolved and over what distances. Within this article, we provide a description of WFE, examples of scenarios in which it is especially important, and opportunities for accounting for it in next-generation models.

Background and challenges with existing approaches

Current operational models are based on unrealistic assumptions (12) and/or empirical observations that are increasingly less representative of current conditions. These assumptions extend back to the 1970s (13–15), when fire modeling was driven by the need to predict head fire spread but was severely constrained by the limited computational capacity of the times. This focus on idealized and simplified scenarios created tractable experimental designs, reduced model complexity, and lowered computational costs appropriate for the technology of the era. For the past half-century, conceptual models of idealized head fire behavior have been used to translate laboratory and, more recently, field observations into wildfire behavior predictions given localized fuel, slope, and ambient wind conditions (3). However, the continued focus on this idealized paradigm, in which all fire is assumed to spread like an isolated perfectly straight head fire, or ellipse, now limits a holistic understanding of wildland fire behavior (12).

The development of operational fire models has relied on assumptions associated with idealized isolated head fire behavior, while disregarding nonlinear effects of fire shape, environmental heterogeneity, and interactions among multiple fires (3). Because fire shape, continuity, vicinity to other fires, and associated inflow patterns control fire behavior through WFE, models without explicit accounting of WFE are inadequate for many critical fire applications, including prescribed fire planning, fire spread in heterogeneous settings, evaluation of fuel treatment effectiveness, fire-effects prediction, and understanding landscape resilience. Incorporating WFE allows for critical and robust reframing of wildland fire behavior research in which fire can be approached as a dynamical system that accounts for the interdependence of local and nonlocal wildland fire-atmosphere-environment processes (12). There are models, CAWFE (16), WRF-SFire (17), WRF-Fire (18, 19), which are increasingly approaching operational viability, that attempt to represent influences of large-scale (tens to thousands of meters) nonlocal fire/atmospheric feedbacks. These tools couple an operational model (13) to a numerical weather prediction (NWP) fluid dynamics model. However, because of their underlying fire spread formulations, vegetation representation, and resolved spatial resolutions, these approaches still cannot fully capture WFE at fire line or fuel heterogeneity scales.

In the past decade, buoyancy, or the tendency for dense materials to displace (and thus push upward) less dense material, has been emphasized as the dominant element in determining local fire processes and fire behavior (11). Plume rise above fires is a well-established concept with much research and modeling associated with it (20), but this upward motion above the region of combustion alone does not adequately explain fire behavior, which depends on the full 3-dimensional (3D) nature of the surrounding wind field. Buoyancy-induced indrafts or entrainment play a role in flame tilt angle and flame length even in idealized or 2-dimensional combustion environments (21). WFE, which forms around the base of a buoyant column and is structured by the fire's surroundings, determines the 3D structure and motion of air influencing fire spread. While buoyancy is a critical initiating condition, WFE phenomena are further controlled by the nonlocal variation of the fire environment that structures flow such as heterogeneous canopy drag (22), fire line geometry (23), and the slope and curvature of terrain (24, 25).

Observation-based characterization of the 3D, multiscale, and often asymmetric buoyancy-induced motion that connects local fire activity and its surroundings atmosphere has been limited by a lack of field-scale experiments across the range of wildland fire configurations and by physical constraints associated with wind tunnel studies (7, 23). The multiscale nature of WFE resulting from fire environment heterogeneities are often absent or heavily constrained in wind tunnel studies. However, a better accounting for the multiscale nature of WFE could help connect wind-tunnel phenomena to realistic wildland fire scenarios.

Wildland fire entrainment

Entrainment in fluid dynamics is the process by which a fluid is drawn into flow patterns associated with nearby fluids (26, 27). Shear-induced entrainment commonly acts on smoke plumes, entraining fresh air into a plume above the combustion zone (20); however, WFE is a separate phenomenon consisting of near surface air flowing in from outside the zone of combustion due to the pressure gradient created by buoyant updrafts (Figure 1). The way that fire induces WFE through buoyancy can be thought of in the following terms. When an unconstrained parcel of air is heated by fire, it expands to a larger volume with a lower density. The weight difference between the ambient air and the lower-density heated parcel results in an upward force on the lighter, warmed air as the heavier ambient air displaces it. The relative weight of the ambient air (heavier than the heated air) pushes up on the lighter air and accelerates it upward and thus induces upward momentum of the rising column (buoyant rise). As heavier air slides under heated air, more distant air parcels move to occupy the volume vacated by the air sliding under the heated column. Through this process nonlocal parcels of air begin to move in response to heating. The strength of buoyant forcing and vertical acceleration of air above the fire is tied to the WFE processes through variations in the spatial density of heat release, which is influenced by fire geometry, fuel arrangement, and oxygen supplied to the fire. This movement is not constrained to horizontal planes and thus WFE is inherently 3D.

As heated air rises, starting with zero vertical velocity, it accelerates for some distance upward until mixing with the surrounding air brings the vertical forces into balance and eventually causes it to decelerate. The spatial extent and pattern of WFE depends on the volume, its rate of vertical acceleration, and the

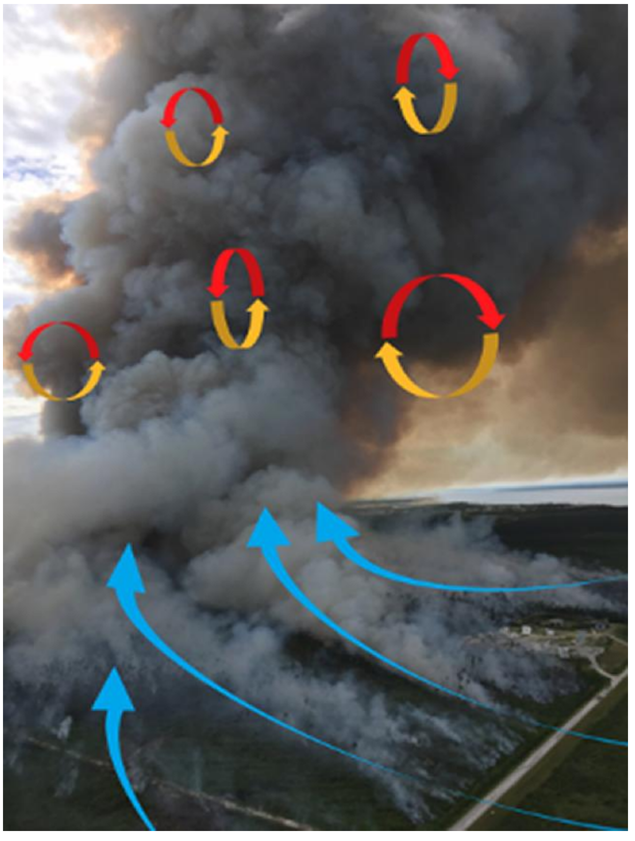

Fig. 1. The smoke plume from a 300-ha prescribed fire at Tyndall air force base, Florida (USA) provides a visual representation of WFE and visually distinguishes WFE (arrows shown at the surface and base of plume in blue) from shear-induced entrainment (arrows within plume at the top of this figure in red/orange), which occurs as the rising plume interacts with the surrounding air. Structure and patterns of buoyancy-induced WFE are a result of ignition pattern (in this case, a mass ignition using a helicopter), terrain, roads, vegetative drag, wetlands, and ambient surface winds (photo courtesy of J. Kevin Hiers). The curvature of the arrows associated with shear-induced entrainment (top) and WFE (bottom) are examples of fire-induced changes in the vorticity field.

height over which the heated air parcels are vertically accelerating. These distances are a function of the feedbacks among combustion, heat transfer, mixing, atmospheric stability, proximity to the surface, and strength of WFE itself. Two-way feedbacks between fire behavior and the dynamic fire environment through WFE mean that these factors cannot be treated independently. The path of the horizontally entrained ambient air toward the vertically accelerating air depends on the nature of and heterogeneity of the surrounding fire environment (22), which in turn influences the vertical extent of the acceleration and thus the vertical distribution of WFE. Although WFE and its controlling factors could be included as independent variables in a simplified fire behavior model, capturing the self-organizing nature of WFE influences on the 3D winds requires a more holistic integration of WFE within a dynamic fire environment.

One way to understand the self-organizing nature of WFE is through vorticity (the curling or rotation of a fluid resulting from local instabilities), which occurs in the atmosphere when shear forces, topographic obstructions, density gradients, and macroscale circulation patterns are present. WFE is the response to density gradient-induced vorticity generation along the fire perimeter. Buoyancy-induced flows in a wildfire alter the direction and local magnitudes of this rotation while generating additional vorticity (Figures 1 and 2) (28). Because these changes in vorticity are consistent with the induction of indrafts (i.e. air drawn into the base of the fire, or interaction with ambient shear and turbulence patterns), the WFE field can be thought of as the fire-induced modification of the ambient vorticity field. Vertical diffusion flame-induced vortex development was observed as early as 1984 (29, 30). More recent work on vorticity-driven lateral spread in complex topography (31, 32) highlights the importance of this concept.

Convective heat transfer

Convective heat transfer occurs when winds carry air past vegetation that is of a different temperature. The wind-fire environment plays a crucial role in shaping the morphology of wind fields around a wildfire. As a result, WFE is a primary factor that determines the nature of convective heat transfer, which is the dominant mode of heat transfer driving wildfire spread (7, 11, 33, 34). Convective heat transfer can act either as a heating agent, promoting fire spread, or as a cooling agent, retarding the fire's movement. This creates a cyclic relationship in which ambient wind conditions, topography, and vegetation structure determine the fire's shape and energy output since all contribute to perturbing the WFE pattern. In turn, the WFE pattern shapes the evolution of the fire's geometry, intensity, and even the WFE itself. This cyclical interaction results in the WFE dictating key fire processes and, consequently, the overall fire behavior.

How WFE connects fire to its nonlocal surroundings

The volume of buoyant air rising from a fire depends on the area and heating rate of the air, the atmospheric conditions, and the supply of air to continuously push the lower density parcel upward. Ambient winds provide some of this supply, but indrafts (WFE) supply the remainder (35), which are shaped by the heterogeneous nature of the fire environment. Aerodynamic drag from both vegetation and topographic barriers constrains the air flow from certain directions and increase the draw through less obstructed paths. Indrafts induced by fires at other locations can also compete for air with other indrafts through these lower resistance paths. For fire scenarios with heterogeneous fuels, topography, multiple fire lines, or curved or broken fire lines, it is essential to account for WFE. In these ubiquitous situations, WFE effects are not uniform and create complex spatially variable fire behavior as opposed to the uniformity inherent in idealized isolated, long, straight fire lines.

Prescribed fire ignition patterns are designed to exploit WFE by shepherding winds to achieve the desired control and fire behavior objectives. When fire lines approach each other, their competing indrafts start to influence the overall WFE patterns. As these WFE patterns from multiple fires combine, a deficit in the pressure field develops between them (Figures 3 and 4) (17, 36), analogous to how sucking on both ends of a straw decreases the pressure inside the straw and neither end is able to suck fluid. The inability to efficiently draft air as efficiently from between two fire lines compared with the directions open to ambient air results in an imbalance between the indrafts, creating a pattern of WFE that rapidly drives fire lines together (37).

For surface fires, the ground inhibits air flow from below, so the winds flowing into the vertically accelerating column near the ground are focused into a hemispheric region above the ground surface (Figure 1). The influence of this inhibition was highlighted by the experiment of Zhou et al. (38), in which upslope fire spread

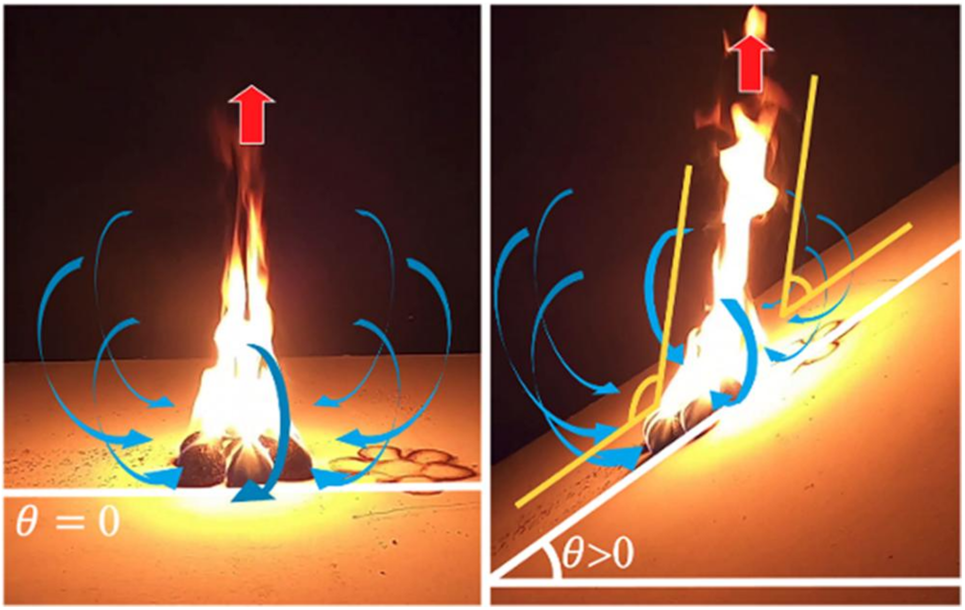

Fig. 2. Conceptualized WFE at the base of a fire on flat ground (slope angle $\theta = 0$) (left) and on a slope with slope angle $\theta > 0$ (right) shows wind velocity vectors associated with entrained indrafts (shown using curved arrows in blue) and buoyancy-driven rising air (upward arrow at top). The effect of topography on the entrainment patterns is illustrated by the imbalance in the entrainment velocity field on the downslope side compared with the upslope side. The angles on either side of flame on the slope (in orange) illustrate a cross-section of the solid angle available for entrainment on the downslope and upslope regions of the fire.

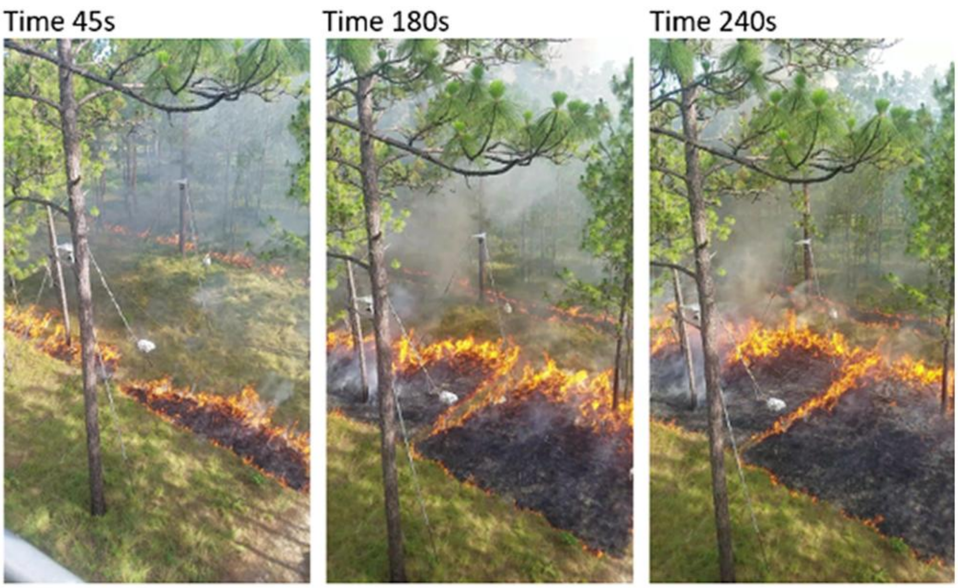

Fig. 3. A simplified ignition pattern of 2 head fires illustrates WFE influences on fire spread over the course of 4 minutes. First, the upwind ignition line entrains ambient flows, stalling the forward spread of the downwind line (seen by the much greater spread distance of the upwind fire in the foreground compared with the downwind fire in the background). Further, a fine-scale discontinuity of fuels creates a break in the upwind fire that develops into a seam between two flanking fires. As the upwind fire line continues to spread as a head fire with the ambient wind, the entrainment patterns of the flanking fires draw them together, spreading perpendicular to the direction of ambient flow (photos by J. O'Brien).

was heavily influenced by entrained air flowing below and through their experimental burning platform. The ground surface also shapes the WFE field as slope and other terrain features channel or constrain indrafts from various directions. In the case of a slope (Figure 2, right), the area through which air can be drawn into the base of the fire is smaller on the upslope (right side of the fire) side compared with the downslope side (left side of the fire). This WFE imbalance pushes the rising hot air closer to the upslope surface further enhancing buoyancy-entrainment feedback (24). However, the strength of the resulting WFE imbalance and associated fire's response depends on the fire's geometry, so even simple slope effects on fire spread cannot be captured with slope-driven correction factors alone. By focusing on WFE, it is possible to predict a fire's tendency to move uphill in response to the imbalance in indrafts as structured by the surrounding environment and based on fundamental principles, as opposed to the overly simplified parameterizations in current operational models.

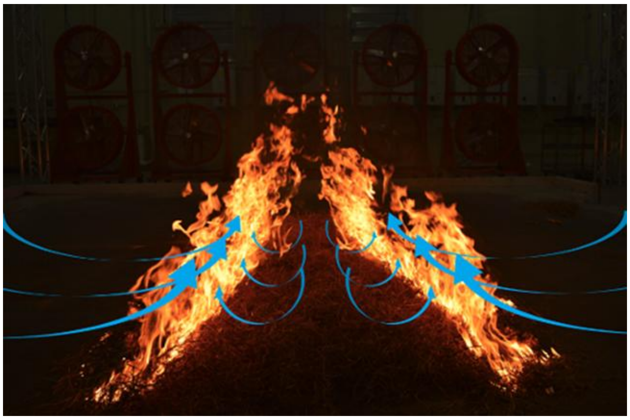

Fig. 4. Illustration of WFE-induced draw between two flanking fire lines (these lines are parallel to each other and the line of sight through the middle of the image, even though the parallax makes them appear as though they converge). When two fires are within the L_E of each other, the competition between WFE from the two fires in the space between them limits the strength of entrainment into either fire from the interior space. The entrainment from the exterior spaces (left and right of the fire lines, respectively) can become stronger than the entrainment to either fire line from the interior space (photos by J. O'Brien).

Heterogeneities in vegetation, arising from fuel dynamics, disturbance, and management such as forest thinning, road cuts, or fuel breaks, induce flow heterogeneities and vorticity features in the ambient flow (8, 39, 40). When the buoyancy-induced motion interacts with these vegetation-induced flow features, the WFE patterns can modified fire behavior in complex ways. Vegetation's influence on WFE is dynamic, as a fire consumes vegetation, forming a fuel density gradient between the region behind the fire to the front of the fire where the vegetation is intact (41). Vegetation consumption by the fire then creates an imbalance in the WFE field, and heat transfer is directed toward unburned fuel. Understanding the influences of heterogeneous vegetation on WFE, especially near the edges of burn areas and adjacent to containment lines, would assist prescribed fire planning and operations in identifying areas where these interactions could lead to the fire escaping containment.

In addition to the patterns of vegetation (40), topography (24, 42), and fire line geometry (43), characteristics of the ambient atmosphere influence WFE flow patterns (h). When ambient winds cause a flame and near-surface plume to lean to one side, the entrainment balance is changed, constraining air movement on the downwind side, while the upwind side remains unconstrained and WFE is strengthened. For many wildland fire scenarios, the WFE flows and ambient wind direction are not parallel, and their interaction drives complex flows and heating patterns. This interaction results in spread evolution that is different from that of a fire line aligned perpendicular to the wind (43). Unfortunately, parallel alignment of wind and slope with fire spread is an underlying assumption for operational fire spread models, such as the Rothermel model (13), meaning that these models are applied to many scenarios without accounting for the impacts associated with violating key underlying assumptions.

Even in the simplest case of a straight-line surface fire in calm conditions, factors such as localized wind gusts or fuel heterogeneity can perturb the idealized WFE patterns, often creating dynamic points of concentrated entrainment and variations in intensity and spread rate. Variation in fire spread creates subsequent heterogeneities in fire line depth and geometry. Fireline depth further influences WFE by resulting in a larger volume of buoyant air and the indraft competition from nonlinear fire lines. Such patterns of fire and environmental heterogeneities constantly interact through WFE dynamics.

When and where are nonlocal influence and WFE important?

The relative importance of nonlocal influence and the need to explicitly account for WFE for accurate fire behavior prediction varies with the relative strength of ambient winds vs fire-induced winds, which is characterized by a Froude number (Fr) (44, 45). For example, in the special case of a single line of low-intensity fire burning under high ambient winds in light fuels (Fr > 1), much of the supply of air under the rising column is supplied by ambient wind. In this case, the motion of surrounding air and thus fire spread (9) is dominated by the ambient wind flow rather than by WFE. However, even in a high-ambient-wind, single-fire line scenario, any variation in fuel loading, especially an increase, will result in deeper fire lines and greater heat release, and increase the influence of WFE on the direction and speed of fire movement. In lower ambient wind scenarios (Fr < 1), such as those under which prescribed fires are often executed, the importance of WFE is magnified, making the incorporation of WFE into fire behavior prediction tools meant to support prescribed fire planning essential.

WFE is driven by the strength of nonlocal dependence, which determines the distance over which these influences can be felt. This distance can be predicted with an entrainment length scale (L_E) to describe how far WFE patterns extend or, alternatively, how far from the fire the environment still affects its behavior. L_E can be thought of as the approximate radial range out to which the fire-induced indrafts cause notable deviations from ambient wind speeds and directions. L_E is linked to the volume and rate of heated air being pushed up and the nature of the fire environment from which air is drawn. For low intensity backing or flanking fires, L_E might be smaller than a meter, but for intense pyroconvection fire scenarios, L_E can be multiple kilometers (46). Examples of the ways the fire and its environment affect the entrainment length scale are (i) increasing size or intensity of fires leads to larger L_E for a given wind speed, (i) increasing ambient winds leads to shorter L_E because the ambient wind supply more air to balance the pressure gradient below rising column, (iii) spatial variation in vegetation structure or topography can create variability in the L_E in different directions, and (iv) atmospheric stability damps the vertical acceleration of the rising air, reducing the range over which air must be entrained. It is important to note that these factors are not independent and must be considered in an integrated fashion. Some examples of coupled effects include higher ambient wind speed, which tends to decrease L_E, leading to deeper and more intense fire lines, which then increase L_E, or drag-inducing canopy structures that reduce L_E but also decrease the influence of ambient winds above the canopy on the wind field at base of the fire. This, in turn, concentrates the WFE in the space below the canopy and increases surface-level horizontal L_E (40, 47).

The strength of the indraft at any location around the fire depends on the spatial arrangement of the active fire area, vertical acceleration of heated air, and resistance to indrafts. When flow is obstructed from one or more directions by topography, vegetation, other indrafts, or atmospheric stability, the indrafts and L_E will increase in the other directions (48). Fire shape, and specifically the ratio of fire perimeter to fire area, also influences L_E. For a given area burning, fires with a long perimeter, such as long thin fire lines, yield a smaller L_E with lower indraft speeds than shorter and deeper fire lines. This is related to the concept poised by (49) that ties the dilution of the buoyancy (and potential formation of intense pyroconvection) to the ratio of the fire perimeter to the area of the fire. This dilution is highest when the entrainment is most efficient and L_E is shortest. A circular fire is an extreme example with the lowest possible perimeter-to-area ratio. New metrics such as a geometrical factor of fire perimeter per unit active fire area must be considered for any parameterization of L_E for use in simplified fire spread models that incorporate WFE.

Pattern dictates process: how entrainment governs fire spread

All wildland fires consist of irregularly curved fire lines–often with discontinuities and variations in fire line depth (50). Such heterogeneous fire geometries can initially emerge from variation in the fire environment (winds, fuels, topography, etc.) or through management actions (i.e. choice of fire ignition pattern in prescribed fires or various suppression tactics). When the curvature of the fire line becomes sufficient, the strength of the WFE-induced flow between the portions of the fire line can exceed the ambient wind and induce spread in directions other than the mean wind direction (43, 51). The spread of flanking fire (fire lines parallel to the ambient wind) is highly sensitive to WFE because it is not spread by the ambient wind. When other portions of the fire line compete with flanking fires for indrafts, WFE can either stop or accelerate their lateral spread.

Observations (Figure 3) have shown that in scenarios in which two flanking fires get sufficiently close to one another (within the sum of their L_E), WFE moving perpendicular to the ambient winds pushes the fire lines together and induces fire intensities greater than nearby ambient wind-driven head fires (52). This interaction between multiple fires can influence the behavior of a new ignition (e.g. a spot fire) if it is sufficiently close to the main fire and within its L_E. This might slow its downwind spread rate or even draw it against or across the ambient wind toward the main fire. The scientific basis to support decisions associated with many tactical fire management practices, such as "counterfiring" operations, in which additional fire is ignited as a suppression action, depends on the ability to anticipate the WFE-driven interaction between multiple fires (53–55). The key to success in these operations is the appropriate assessment of the L_E for the specific fires and fire environments. When counterfires are attempted outside of this length scale, the new fire can begin to spread independently, creating disastrous results (56).

Prescribed fire scenarios present potentially the most striking illustration of the influence of WFE on fire behavior as practitioners engineer the flow patterns by deliberately igniting in specific patterns (57). Prescribed fires are seldom individual straight lines, as practitioners use curvature and multiple-ignition patterns purposefully to engineer the fire behavior by guiding the entrainment patterns (3), inducing either competition between indrafts or openings for fresh air entrainment (Figure 4). Practitioners can adjust fire activity in real time by igniting the gaps between the fire lines at the edge of the area being burned, (i.e. "sewing up the flanks" in local vernacular), reducing fresh air indraft and increasing draw between the fire lines. These tactics are currently guided by practitioner experience and intuition; however, including WFE in fire behavior prediction tools could provide appropriate decision support for prescribed fires.

A new paradigm: accounting for nonlocal influences

Current operational tools predict fire activity at any location based solely on conditions at that location. Even though such tools can be calibrated for predictions in idealized scenarios (e.g. long line fires), it is impossible for these tools to explicitly account for nonlocal influences of fire line geometry, interaction between multiple fires, or nearby/adjacent fuel or topographic heterogeneities. Such descriptions of nonlocal environment or fire line features are not even inputs for these tools. Without a paradigm shift toward a more explicit accounting of nonlocal interactions driven by WFE, opportunities to increase the accuracy of fire behavior predictions will remain limited. Accounting for WFE requires integrating the nonlocal influences of the surrounding heterogeneous and dynamic vegetation structure, ambient wind, fire patterns on the landscape, topography, and fire-influenced fluid motion, within a range L_E around a fire. This nonlocal integration can be achieved through explicit modeling of fire-atmosphere interactions or potentially through reduced-order parameterization of the WFE phenomenology or artificial intelligence (AI)/machine learning (ML) approaches.

To account for WFE, some wildland fire models are using a multiphase computational fluid dynamics (CFD) approach to explicitly represent 3D vegetation structure and resolve fundamental fire processes at meter-scale resolutions (23, 58, 59). Such tools inherently capture the influences of fire pattern, 3D vegetation, and atmospheric feedbacks (60) that structure WFE and subsequent fire behavior (Figure 5). Their ability to represent nonlocal influences of fire geometry (43), interaction between multiple fires (53), vegetation (8), and topography (24). Because the ability of this class of tools to capture WFE is potentially their most robust component, they can also be used to explore and potentially develop metrics signifying the importance of WFE in various fire scenarios.

Although physics-based CFD tools are useful for understanding the mechanics of WFE and provide the flexibility to account for a wide range of heterogeneous factors, their significant computational cost currently limits their utility for operational support (61). Thus, there is a need for less expensive approaches to capturing WFE influences, even if they are not as general.

There have been theoretical 1-dimensional (1D) fire spread modeling efforts that recognized the importance of entrainment or fire-induced winds as a key factor even in the infinitely long head fire scenarios (62) and empirically based 1D models implicitly account for mean entrainment perpendicular to the straight fire line. However, the 1D nature of these effort restricts them from representing the broader implications of WFE associated with fire geometry or landscape heterogeneity. The amount of error associated with the 1D entrainment restrictions for predictions of fire behavior in realistic fire scenarios depends on the fire scenario (ambient winds, fuel loads, fire intensity, fire geometry, etc.). One example in which WFE is dominant is in a ring fire scenario, in which the fire-induced winds pull in from all sides (63) and can stop any substantial fire spread in the downwind or outward radial directions. Current operational models have no way of capturing this effect of convergent entrainment, as it originates from the 3D nature of the flow field around and inside the ring.

The dynamic and multiscale nature of WFE complicates the development of generalized (applicable to wide range of fire scenarios) alternative modeling approaches. The importance of the 3D nature and spatial extent of WFE, L_E, not only depend on the fire scenario, but also can be different for different portions of a fire and evolve with the fire. This makes it difficult to identify a

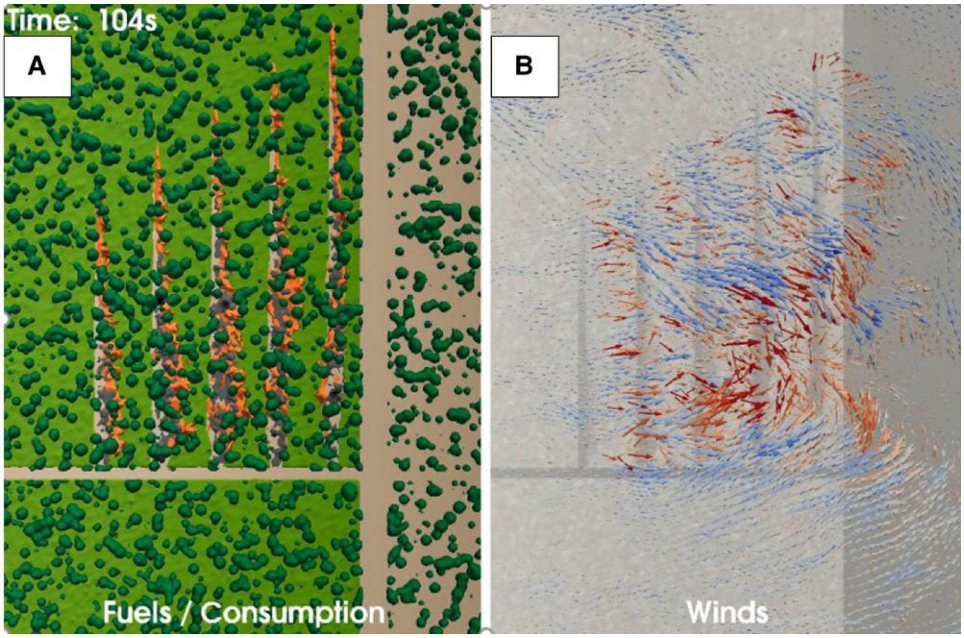

Fig. 5. Numerical simulation results from a coupled fire-atmospheric model, FIRETEC, illustrate the dominance of WFE in a 5-line prescribed fire in a longleaf pine forest. (A) Consumption at 104 seconds into the simulation and (B) the wind vectors at the same moment 2 m above the surface (ambient winds are moving left to right). Blue arrows show downdrafts; red arrows are updrafts, and vectors are sized based on the velocity. Of note is the channeling of flow along roads, creating curving flows around the corner of the unit entrained by the convective core of converging fire lines. The interaction between the interior lines creates a converging plume behavior and the draw between the lines minimizes the downwind (to the right) spread of the rightmost line. Unburned vegetation upwind creates drag that structures WFE with reduced flow (FIRETEC simulation and visualization courtesy of Alexandra Jonko).

priori the scales of WFE. However, some clues, such as the anticipated macroscale character of the fire (e.g. fire size or intensity, ambient wind speed, topographic scales), can suggest the order of magnitude for dominant WFE scales, the importance of WFE pattern, and options for representing important aspects of WFE for various classes of fires. In large intense fires, for example, dominant WFE patterns and L_E can be hundreds of meters to kilometers in scales and the finer-scale details of the WFE pattern can have reduced impact. In these scenarios, many of the important WFE phenomena can be captured by coupling simplified spread models [e.g. (13, 64)] to NWP models, such as in CAWFE (16, 65), WRF-Sfire (17), and WRF-Fire (18, 19). These NWP/Fire approaches, which are still research-oriented models, capture nonlocal influences of WFE with length scales between the computational mesh resolution (typically tens to hundreds of meters) and L_E (hundreds of meters to the kilometer scale). For large fires, this approach, which is less computationally expensive than the physics-based fire/CFD approach described previously, can capture influences of curvature in topography or large-scale fire shape patterns, which feed back on the fire through the wind field.

Within current NWP/Fire models, the underlying fire behavior models are still 1D in nature, and fine-scale fuel structure and heterogeneity is not represented. Consequently, their applicability should be challenged in scenarios in which fire lines have a radius of curvature that approaches ∼10× the fire line depth, or in which fine-scale fire line curvature, topography, fuel heterogeneity, or interaction between multiple fires are expected to be significant. For example, these tools may struggle to predict fire behavior for a low-intensity prescribed fires in which the interaction between multiple, often oblique fire lines, vegetation structure, and heterogeneity can have a large impact. To predict fire behavior in scenarios in which fine-scale heterogeneity, multiple fire lines, or counterfire operations are important, models ideally need to account for the 3D vegetation structure and WFE. There is an opportunity not only to use the NWP/Fire approach to explicitly resolve the large-scale WFE influences, but also to replace or augment the underlying empirically based 1D fire spread models with parameterizations that would capture smaller-scale WFE impacts of specific fire scenario features. For example, a reduced-order model or parameterization could be added to account for under-resolved fire line curvature or macroscale fuel discontinuities.

A promising opportunity to improve operational models while avoiding the computational costs of CFD tools lies in recently developed reduced-order formulations designed to capture coupled fire-atmosphere interactions. Examples include QUIC-Fire (36, 66, 67) and pyrogenic potential (68). These models are formulated using reduced-order representations of physical processes to circumvent some of the most computationally burdensome aspects of full CFD models while still capturing the influence of WFE on fire. Although they do not capture all details resolved by CFD tools, they inherently avoid the assumptions of the 1D fire spread approaches and capture the combined influences of the fire-induced local and nonlocal winds. In the development of new modeling tools, target applications are often identified, which influence the types of simplifications or limitations that are acceptable. For, example, to preserve the ability to resolve influences of 3D fuel structure and fine-scale fire-geometry impacts, QUIC-Fire was designed to use resolutions of meters and thus becomes computationally burdensome for large wildfires. The theoretical basis for these models typically lends itself to continual advancement as additional aspects of fire or atmospheric physics are identified, such as the addition of vorticity influences to pyrogenic potential (69), in hopes of being able to represent vorticity-driven lateral spread phenomena without full CFD.

The advancement of computation and data storage capacity have opened up the potential for using AI and ML to parameterize the influences of WFE and augmentation limitations of capturing WFE in 1D fire spread or approaches with course resolutions. By leveraging some combination of observations, CFD simulation results, and even reduced-order coupled fire-atmosphere model results to develop a training set of sufficient breadth, AI/ML algorithms may be able learn the essential dependencies of WFE on the nonlocal aspects of the fire environment. However, number of degrees of freedom in describing the fire environment or dimensionality of the parameter space that must be covered by the training data set is immense, and careful testing and updates to models will be needed. Despite these cautions, we believe that this is a promising approach to account for fire geometry, nonlocal aspects of vegetation, and topographic heterogeneity without explicitly simulating the wind field at those scales. Using AI/ML-built parameterizations of unresolved WFE effects would be one way to augment NWP/Fire modeling approach to overcome the limitations of the 1D fire spread model and under-resolution of the atmospheric motion.

Model validation is a significant challenge for all types of wildland fire behavior models due to the wide range of fire scenarios and difficulties in adequately characterizing fire environments and behavior. The influences of WFE are especially challenging to evaluate, as they depend on the spatial and temporal variability in the fire environment. The underlying methodologies used in CFD models have had various levels of evaluation for various scenarios, some of which can be translated to the WFE processes. This is not meant to imply that CFD tools are validated for all aspects of WFE, fire behavior, or combustion. Because models like WFDS and FIRETEC are expected to capture a range of WFE effects across scales ranging from a few to hundreds of meters, these tools could be compared with NWP/Fire models, reduced-order models, or even AI/ML parameterizations for various fire scenarios to quantify the skill of these other approaches to capturing WFE in various fire scenarios. However, all these approaches represent the fire spread and energy-release patterns slightly differently even with the same WFE, such that care must be taken to identify the differences between the WFE representation vs underlying fire spread.

With the recognition that WFE is a critical driver of fire behavior and that nonlocal influences should be accounted for, new kinds of observational data to support either model development or model validation are needed. By growing the focus of data collection from local fire environment and fire characterization to include the context of data collection in terms of vegetation, topography, fire geometry within L_E of measurement sites, WFE phenomena can be studied and understood. Spatially distributed measurements of dynamic winds within L_E of fire observations will also be valuable. Additionally, there is an opportunity for such measurements to help identify rules of thumb for L_E based on fire behavior and fire environment. Lack of repeatability of wildland fire field experiments often drives the need for laboratory studies, but even in laboratory studies there may be opportunities to characterize fine-scale WFE and use WFE to understand the implications of constrained experimental design.

It should be recognized that although WFE is important for understanding fire behavior under specific conditions, accounting for WFE will not improve all wildland fire decision support products equally. For example, when mapping fire hazard potential, the rankings are not tied to specific fire scenarios, but instead their primary focus is in providing relative comparisons at broad scales. Without accounting for scenario specifics (e.g. direction of spread, ambient wind speed, or shape of fire line), WFE cannot be properly determined and is not as relevant (with the possible exception of the influences of particularly complex and dominant topographic features).

Conclusions

Climate extremes will increasingly challenge fire suppression, impact communities, and degrade ecosystems. Addressing this growing risk through proactive management solutions that protect society, ecosystems, and watersheds requires improved fire behavior prediction capabilities. Transformative advancement of these capabilities is possible through the description and incorporation of WFE as the dominant phenomena controlling a fire's nonlocal interactions with its inherently heterogeneous environment. WFE exposes fundamental shortcomings associated with applying fire spread parameterizations, or even theoretical constructs, based on an idealized long linear fire front perpendicular to the ambient wind. Wildland fire models without a way to account for WFE will continue to be limited in their potential to account for the influences of complex terrain, heterogeneous vegetation, or realistic fire geometries.

WFE determines how fires respond to heterogeneous fire environment (vegetation, ambient winds, topography, and fire geometry) through the fluid dynamic motions of the surrounding atmosphere over distances tied to an entrainment length scale (L_E). Put simply, the patterns of heterogeneity contained within the wildland fire environment itself govern the process of fire spread and behavior through WFE. The patterns of entrainment are often not isotropic, and this length scale depends on the intensity and geometry of the fire as well as on the fire environment. WFE's linkage between fire and its context make it the critical bridge from laboratory investigations or idealized field measurement campaigns to naturally occurring wildland fires. WFE is the underlying mechanism through which prescribed fire behavior and effects are engineered and is thus necessary to support the fire community's desire to expand the pace and scale of prescribed fire in fire-prone ecosystems. To capture the influence of WFE on fire spread, 3D vegetation structure, topography, and the activity of nearby fire lines must be incorporated into the dynamic fluid dynamic response of the atmosphere surrounding the fire.

A significant shortcoming of current operational fire behavior models and their underpinning wildland fire theory is their lack of interdependencies between fire and the nonlocal surroundings. The processes underpinning existing operational fire models are local in nature and are thus insufficient to robustly predict real-world fire spread patterns in which heterogeneities dominate the fire environments. These deficiencies are magnified in critical situations of most interest to fire practitioners, such as where fire activity occurs in highly heterogeneous conditions, under dynamic wind conditions, during counter fire operations, planning for novel climate scenarios, and all prescribed fire planning (3, 41). Fortunately, several methods for accounting for WFE have emerged, including many CFD models and reduced-order fire models. Such tools already include coupled-fire atmospheric feedbacks that implicitly recognize WFE or can be modified to incorporate it. Thus, one option for better inclusion of WFE in operational decision support may be finding ways to move these models or ideas learned from these tools toward operations. Understanding and accounting for WFE as the mechanism by which fluid flow governs heat transfer and combustion dynamics will enable a more robust prediction of wildfire behavior, fire mitigation options, safer planning of prescribed fire, and improved training to address the wildland fire management in a rapidly changing future.

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Data statement

There were no specific data used directly in the development of this manuscript.

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