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Large Outdoor Fire Modeling (LOFM) Workshop Summary Report

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Abstract

On March 18-19, 2019, NIST held a workshop on Large Outdoor Fire Modeling (LOFM) to assess the state of the art in computational fire modeling and to identify a set of research priorities for driving progress in the development of large outdoor fire models. This workshop was broadly concerned with large outdoor fires that have the potential to negatively impact communities or the environment. In this context, wildfires, wildland and wildland-urban interface (WUI) fires, post-earthquake fires, oil spill cleanup, and community-scale structural conflagrations may all be classified as large outdoor fires. The premise of the workshop was that modeling tools may assist in mitigating the large outdoor fire problem or at least in developing a better understanding of the problem.

The group looked at the modeling problem in three different areas: (1) operational modeling, (2) forensic reconstruction, and (3) planning, such as prescribed burns or forest fuels management. Operational models—mostly empirical rate of spread models—were classified as running much faster than real time, with simple user interfaces. These models are useful for forecasting and generating large ensembles of fire scenarios for risk analysis. Forensic models usually need to be run at landscape scale to capture terrain features and incorporate weather effects. High-fidelity, physics-based models may be used for understanding detailed phenomena, forensics, or for planning purposes. The physics-based models tend to be limited by the level of resolution available for input parameters and by the stochastic and chaotic nature of real fire events. A survey of available models is presented in this report.

Approximately 50 onsite and 20 online attendees participated in the workshop. Plenary presentations where given by Chris Lautenberger of REAX Engineering, Janice Coen of the National Center for Atmospheric Research, and Rod Linn of Los Alamos National Laboratory. These lectures laid out the state of the art in operational rate of spread models, fire-weather interaction, and physics-based models, respectively, providing a baseline for workshop discussions. Details of the workshop process are given in the report. Three breakout groups, each with a balanced makeup of fire-related expertise (from first responders to high-performance computing experts), convened to address user needs, identify research gaps in outdoor fire models, and to suggest a set of grand challenge problems to focus research efforts with a ten year horizon.

Key words

Atmospheric flows; digital elevation model; disaster resilience; fire emissions; fire growth; fire plumes; firebrand generation; emergency response; fire-weather coupling; forecasting; forensic reconstruction; fuels data; geographic information system; high-performance computing; large outdoor fire modeling; physics-based fire models; prescribed burns; rate of spread fire models; smoke transport; spot fire ignition; spotting; structure ignition; terrain; vegetation; wildfires; wildland fire; wildland-urban interface; wind tunnel experiments.

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The art of modeling is not to produce the most comprehensive descriptive model but to produce the simplest possible model that incorporates the major features of the phenomenon of interest. – *Howard Emmons*

1. Introduction

On March 18-19, 2019, the Fire Research Division of the Engineering Laboratory at NIST held a two-day workshop on Large Outdoor Fire Modeling (LOFM) in Gaithersburg, Maryland. The purpose of this workshop was to assess the state of the art in computational modeling of large outdoor fires and to identify a set of research priorities for driving progress in model development.

1.1 Background

Large outdoor fires are being studied by the International Association of Fire Safety Science (IAFSS) working group on Large Outdoor Fires and the Built Environment (LOF&BE) [1]. These fires comprise most large-scale fire events that are not localized residential or commercial building fires. In this workshop, we were broadly concerned with large outdoor fires that have the potential to negatively impact communities or the environment. In this context, wildfires, wildland and wildland-urban interface (WUI) fires, post-earthquake fires, oil spill cleanup, and community-scale structural conflagrations may all be classified as large outdoor fires where modeling tools may either help in mitigation or at least aid in developing a better understanding of the problem.

Smoke and emissions from wildfires can have a dramatic impact on emergency evacuation, tactical response to the fire, and also long-range air quality. Transported wildland fire smoke also presents a clear public health danger in both the short and long term [15]. The negative health impacts come primarily from particulate matter and ozone. Large fires[1] have the potential to expose millions of people to hazardous particulate concentration levels [15]. Estimates of health costs from fire smoke vary considerably in the literature, but can range up to tens of billions of U.S. dollars per year [16]. Some studies predict that these costs will increase in the coming decades, including the potential for an increase of thousands of premature deaths traceable to fire smoke by the year 2100 [17].

Smoke modeling and impact prediction is done through frameworks combining fire models with emissions, transport, and dispersion modeling. Examples include the U.S. Forest Service BlueSky framework [3, 4, 5] and the National Oceanic and Atmospheric Administration (NOAA) operational smoke product [6, 7]. Daily forecast runs are available at resolutions down to 1 km. The accuracy of such systems are sensitive to smoke plume injection height [4, 8], which is typically modeled using presumed fire growth and heat release rates of the fires. More detailed and accurate modeling of the overall fire growth

[1]The workshop generally did not focus on pyrocumulonimbus fires (also known as "pryoCb-" or "mega-" fires), which have plumes that reach the stratosphere and hence have the potential for global transport of smoke and emissions [2].

and fire plume would directly benefit smoke impact predictions. A range of alternative smoke transport and forecasting models are being designed and are hoped to become useful in the future [9]. Furthermore, several inter-agency observational field campaigns have been planned to develop or refine chemical species emission factors from wildfires and prescribed fires. These studies aim to cover a range of scales, from small-scale laboratory experiments (SERDP-funded studies [10]) to meso-scale plume dynamics (FASMEE [11] and RxCADRE [12]) to large-scale smoke transport and chemistry (FIREX-AQ [13] and WE-CAN [14]). These observational campaigns are critical to model development and validation.

Fires in wildland-urban interface communities are a rapidly growing problem in the U.S. Six of the top 10 most damaging single wildfire events in the last 100 years in the U.S. are fires that have occurred in WUI communities—all in the last 15 years. Over 46 million homes in 70,000 communities are at risk of WUI fires, which have destroyed an average of 3,000 structures annually over the last decade and is rapidly growing [18]. Wildland and urban fire fighters typically respond to over 80,000 wildland fires each year. The total cost of WUI fires in 2009 was estimated to be over $280 billion [19] and account for over 20 % of fire fighter fatalities. A significant problem is that communities currently lack sufficient resilience [20] to resist and respond effectively to wildland-urban interface fires.

Several strategies or methodologies used in fire protection engineering for the built or urban environments could be used to improve community resilience to wildfires. For example, engineering of materials and novel construction methods could limit structure ignition by firebrands or direct flame contact. Both active and passive fire protection could be used to limit exposure to a structure or community. Risk assessment tools could be used to promote preparedness. And improved policy through implementable codes and standards, education, and training can limit the risk and exposure for first responders and the community at large.

1.2 Fire Modeling Opportunities and Challenges

Computational modeling has become an essential tool for fire protection engineering in the built environment and a central premise of the LOFM workshop was that modeling has an important role to play in addressing issues related to large outdoor fires. The workshop considered three main application areas for modeling: (1) operational forecasting, (2) forensic reconstruction, and (3) planning. Models for operational use run much faster than real time and must be robust and easily integrated into a modeling or decision-making framework such as the Wildland Fire Decision Support System (WFDSS) [21]. Forensic reconstructions may be used to improve phenomenological understanding, for model development, or used in litigation for determining fault for wildfire ignition. Planning applications broadly encompass activities like ensemble runs for risk analysis, predicting the outcomes of prescribed burns, forest fuels management, or planning of experiments for engineering design purposes.

Operational models find wide use in both forecasting of smoke and emissions and in planning exercises. But, in terms of forecasting fire line progression, very few fires are ever modeled. Only 3 % of the fires in the U.S. go over 100 acres and only a small fraction of those get modeled by an incident meteorologist; fires have to last for several days for the output of operational forecasts to have an impact on tactical decisions for fire response [22, 21].

Regardless of the application, the workhorse model in the U.S. for active fire line rate of spread is Rothermel's empirical model from 1972 [23]. The model's simplicity and speed make it very useful for generating a large ensemble of different fire scenarios for Monte Carlo risk analysis. Unfortunately, the assumptions underlying Rothermel's model, such as uniform slope and wind speed, are almost always violated in real fires. One of the key challenges facing the LOFM community is the development of a replacement for Rothermel—a next generation rate of spread model—which incorporates better physics and is therefore more broadly applicable.

The incorporation of more physics explicitly in the model may solve some problems but can create others. Computational fluid dynamics (CFD) models, for example, can readily handle atmospheric physics, turbulence, and heat transfer. However, generally, the higher the fidelity of the model the slower it runs. Furthermore, taking advantage of high resolution requires high resolution input parameters, which may be difficult to obtain. The wildfire community still relies on the Rothermel equation because high-fidelity, physics-based models are not yet provably better in practical applications such as tactical decision-making and forest fuels management. CFD models also present a barrier to use because they usually require specialized background of the user and access to sufficient computing resources. All these issues should be considered when scoping out the target applications for certain models.

Implicit in stating the need for improved modeling capabilities is that the physical processes underlying wildland and WUI fire behavior and smoke generation and transport should be well understood. There are many areas in which our physical understanding is inadequate, and generally there are two schools of thought on moving forward. One view, which is usually the starting point for development of CFD models, is that the fundamental laws (governing equations) for fire dynamics—mass, momentum, and energy conservation—are known, and mathematically filtering these equations to the length and time scales relevant to wildland fires generates unclosed "subgrid" terms that must be modeled. One can choose to study these terms individually and assess the validity of each subgrid model on its own. In this case, experiments or numerical studies used for development, verification and validation, must be designed to target the specific subgrid term in question as well as the large-scale observable. The alternative view, which is usually the starting point for the development of empirical correlations, is to study the dynamical processes underlying wildfire behavior as a large-scale system. One may then develop mechanistic theories (usually starting from the fundamental physical laws) for the observed fire behavior that may lead to many modeling advances, including the very practical. Both approaches rely on accurate, sufficiently resolved initial and boundary conditions. It should be noted that the two view points are not mutually exclusive and, in fact, may even complement each other. Indeed, hybrid approaches are viable and several such coupled models have been developed over the last decade of LOFM research (e.g., CAWFE [24], WFDS-Level Set [25], WRF-Fire [26]).

1.3 Workshop Scope and Objectives

The workshop was convened to identify measurement science needs and inform future research activities in the area of large outdoor fire modeling. Discussions were focused on identifying and understanding technical solutions for large outdoor fires through greater use of existing modeling technologies, development and deployment of new modeling technologies, and the use of modeling in preventative technologies including planning and fire protection design.

Objectives for the workshop included development of:

- a clear statement of why modeling is a useful tool for understanding behavior and mitigating the unwanted effects of unplanned large outdoor fires, and
- a series of grand challenge problem statements for improving large outdoor modeling with a 10-year horizon on research efforts.

Workshop discussions addressed the following aspects of computational fire modeling:

- high-performance computing applied to outdoor fire modeling,
- incorporation of micro-scale and macro-scale weather data and wind-driven fire spread,
- incorporation of topography and terrain features, firebrand[2] generation, lofting, and spot fire ignition physics, and
- large-scale prescribed burn and wind-tunnel experimentation.

1.4 Report Organization and Content

This report describes workshop discussions and documents the contributions of workshop participants in the NIST Large Outdoor Fire Modeling (LOFM) Workshop held on March 18-19, 2019 in Gaithersburg, Maryland. The structure and format of the workshop is described in Section 2. Current models and their uses are described in Section 3. Gaps and prioritized research needs are listed in Section 4. Research plans and grand challenge research statements are provided in Section 5.

The workshop agenda is provided in Appendix B, contributors are listed in Appendix A, plenary presentations are provided in Appendix E, and detailed breakout group assignments are provided in Appendix C.

[2] In this report, the term "firebrand", as opposed to "ember", is used throughout to conform the definition given by [27], quote: *"Ember" refers to any small, hot, carbonaceous particle. Meanwhile, "firebrand" specifically denotes an object which is airborne and carried for some distance in the air stream.*

2. Workshop Overview

2.1 Workshop Format

The workshop format included plenary presentations followed by structured breakout discussions, plenary reporting, and prioritization of findings. The one and one-half day workshop was broadly organized around three areas of fire modeling: operational fire forecasting, forensic reconstruction, and planning. Breakout discussions were focused on defining the need, identifying gaps, and outlining steps to address research needs in each modeling area. The workshop agenda is provided in Appendix B.

Workshop participants included experts in fire science, wildland fire, atmospheric modeling, and high-performance computing communities, and included operational model developers, physics-based model developers, experimentalists, model users, and emergency responders. More than 50 invited and registered participants were in attendance, and workshop plenary sessions were broadcast on NIST Livestream to more than 20 additional participants online. Online participants were able to submit questions through a web application. In-person and online contributors to workshop discussions are listed in Appendix A. Workshop plenary presentations, discussions, and prioritization activities have been archived online and can be viewed at https://livestream.com/nist-el/lofm, password LOFM-fire19.

2.2 Overview of Current Knowledge and Capabilities

Plenary presentations were used to outline the current state of knowledge and capabilities in computational fire modeling and to provide a starting point for more detailed discussions in each breakout group. Overview presentations were provided by plenary speakers Chris Lautenberger of REAX Engineering in Berkeley, California, Janice Coen of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and Rod Linn of Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. Abstracts summarizing the key information in each presentation are provided below. Slides from the presentations are provided in Appendix E.

2.2.1 Applications and Limitations of Current-Generation 2-D Wildfire Models (Chris Lautenberger, REAX Engineering)

The current generation of 2-D wildfire spread models typically integrate separate semi-empirical submodels for surface spread, crown fire initiation and propagation, and spotting to simulate landscape-scale fire spread. Meteorological inputs are often provided via Numerical Weather Prediction hindcasts/forecasts or observations from surface stations. In the United States, surface and canopy fuel input layers are usually obtained from the national LANDFIRE [28] program. Forward rate of spread is calculated at all points along the fire front as a function of surface fuel model, moisture content, topographic slope, and wind speed using a surface fire spread model which, in the U.S., is almost always Rothermel's 1972 model [23]. Spread rate in other directions is estimated by assuming that the fire front, under idealized conditions, would take on an elliptical shape. Current-generation spread models have several limitations. Post-frontal or smoldering combustion are usually not addressed or are accounted for approximately. Particularly in areas with deep duff layers or litter accumulations due to tree mortality, smoldering combustion may contribute significantly to a fire's total heat release, which, in turn, drives plume entrainment. However, most models do not address this fire-atmosphere coupling, which may significantly influence wind conditions, and, therefore, spread rate and direction at the fire front. Recent research has demonstrated that convective heating and ignition of fuel particles, which is not addressed in the Rothermel fire spread model, plays an important role in the physics of fire spread.

Despite these limitations, current-generation 2-D wildfire spread models have several useful applications. They lend well to large-scale Monte Carlo simulations at regional scales because they are computationally inexpensive and, with distributed memory parallelization, nearly perfectly parallel. This has made it possible to conduct "backward looking" assessments of wildland fire hazard/danger/risk by simulating spread of millions of fires under historical wind and weather conditions and quantifying impacts to assets at risk. Similar assessments can also be conducted to quantify near-term (up to 7-day) fire risk by driving a Monte Carlo fire spread model with forecasted, rather than historical, wind and weather conditions. Similarly, such models can be used to forecast the spread of incipient and established fires, which has obvious applications to public safety, including planning evacuations and suppression activities.

The presentation (see Appendix E.1) shows examples some of these applications, including ongoing efforts in California to deploy and test an automated system that will forecast near-term fire risk with greater spatial and temporal fidelity than current approaches, and, once fires are ignited, forecast their spread up to 3 days in the future. Additionally, examples are shown where fire hindcasts match observed spread quite well and where they do not perform well, due to inherent limitations of the models described earlier.

2.2.2 The Design and Application of Numerical Weather Prediction-Based Wildland Fire Models at Landscape Scales (Janice Coen, NCAR)

In kinematic models, wind and other fire environmental factors are specified as external inputs to a collection of fire algorithms. A newer class of models that two-way couple fire behavior with the atmosphere, in which the governing physical laws are represented by a computational fluid dynamics (CFD) model, have shown an increased potential for simulating transient fire behavior and phenomena. When a CFD model is a numerical weather prediction (NWP) model, it is possible that the coupled system can be applied at convective-scale NWP resolution (hundreds to thousand-meter grid spacing) to understand and predict many aspects of overall fire evolution, as well as the complex, rapidly changing fire behavior and phenomena in landscape-scale fires, even when fire processes are parameterized with relatively simple semi-empirical formulae. This is possible, provided that the system captures fire-atmosphere interactions and the intricate, time-varying microscale airflows in mountainous terrain. Such models can be used to investigate how the heat fluxes released by a fire, and atmospheric dynamics and thermodynamics shape fire behavior and effects, and are distinct from (and validated differently from) other finer-scale models and studies that focus in more detail on combustion, heat transfer, and mode of propagation.

In this presentation (see Appendix E.2), the CAWFE [29] coupled weather-fire modeling system is applied to several recent wildfire events, and our ability to reproduce distinctive phenomena and occurrences in these events is examined, along with limitations in our remote-sensing systems, inputs, treatments of fire processes, and meteorological models that add to the apparent unpredictability in forecasting of wildfire events.

2.2.3 Physics-Based Coupled Fire-Atmosphere Modeling: Opportunities and Challenges (Rod Linn, LANL)

Experiments and observations have demonstrated that the two-way feedbacks between fires and atmosphere play critical roles in determining how fires spread or if they spread. Advancements in computing and numerical modeling have generated new opportunities for the use of models that couple process-based wildfire models to atmospheric hydrodynamics models. These process-based coupled fire/atmosphere models, which simulate critical processes such as heat transfer, buoyancy-induced flows and vegetation aerodynamic drag, are not practical for operational faster-than-real-time fire prediction due to their computational and data requirements. However, these process-based coupled fire-atmosphere models make it possible to represent many of the fire-atmosphere feedbacks and thus have the potential to complement experiments, add perspective to observations, bridge between idealized-fire scenarios and more complex and realistic landscape fire scenarios, allow for sensitivity analysis that is impractical through observations and pose new hypothesis that can be tested experimentally. Specific examples of the use of FIRETEC in this fashion include: 1) investigation of the 3D fire/atmosphere interaction that dictates multi-scale fireline dynamics; 2) fundamentals of slope/fire interaction; 3) the influence of vegetation heterogeneity and variability in wind fields on predictability of fire spread; 4) the interaction between ecosystem disturbances such as insect attacks and potential fire behavior. Additionally, coupled wildfire/atmosphere modeling opens new possibilities for understanding the sometimes counterintuitive impacts of fuel management and exploring the implications of various prescribed fire tactics. Results from these studies highlight critical roles played by coupled fire/atmosphere interaction, which is directly affected by the fire geometry, structure of the vegetation and topography. Certainly, there need to be continued efforts to validate the results from these numerical investigations, but, even so, they suggest relationships, interactions and phenomenology that should be considered in the context of the interpretation of observations, design of fire behavior experiments, development of new operational models and even risk management. (see Appendix E.3)

2.3 Detailed Breakout Discussions

To facilitate multi-dimensional, cross-disciplinary breakout discussions, participants were categorized by area of expertise and assigned to one of three breakout groups with approximately equal weighting in each area (approximate because many individuals serve more than one area of expertise). Individuals from the same organization were assigned to different breakout groups. In each breakout, an expert agreed to serve as Chair to lead discussions and report out results, and a facilitator was provided to assist with the discussions and the recording of results.

Breakouts were structured into three rounds of discussion, and participants in each group remained constant over the duration of the workshop. Each breakout group received identical assignments, and were instructed to consider modeling for operational fire forecasting, forensic reconstruction, and planning in each of the following discussion sessions:

- **Breakout Session 1: Defining the Need** – intended to identify needs of end users, how fire modeling serves those needs, and what models are currently in use.
- **Breakout Session 2: Identifying Gaps** – intended to identify the properties of optimal models, gaps between current capabilities and what is considered optimal, and how uncertainty is quantified.
- **Breakout Session 3: Steps to Address the Problem** – intended to outline research needs to address high-priority gaps, and to formulate grand challenge problem statements encompassing prioritized needs.

Focused questions were used to target breakout discussions and more clearly explain the type of information that was being requested. Detailed information on assigned focus questions is provided in Appendix C.

Results were reported and discussed in plenary sessions after each breakout. Gaps (i.e., research needs) that were identified by all the groups in Breakout Session 2 were sorted and consolidated, and the resulting list was prioritized by workshop attendees through in-person and online voting. Highest priority needs were assigned for further discussion in Breakout Session 3 for the groups to complete more detailed implementation plans and to formulate grand challenge problem statements. Following Breakout Session 3, the resulting list of grand challenge problem statements was prioritized by workshop attendees through in-person and online voting.

Results from each breakout session, and the resulting prioritized research needs and grand challenge problem statements are summarized in the chapters that follow.

3. The Need for Large Outdoor Fire Modeling

3.1 Why Large Outdoor Fire Modeling is Needed

The needs of end users, and how large outdoor fire modeling serves those needs, were discussed in each of the three modeling application areas: Operational, Forensic, and Planning. Results are summarized in the sections that follow.

3.1.1 Operational Needs

End users and modeling needs for operational fire forecasting include:

- **Incident commanders/emergency responders** – need faster than real-time information on hazardous materials, smoke, and fire spread on which to base decisions related to evacuation orders, resource management, tactical decisions on suppression activities, and deployment of teams and equipment. Information must be summarized, distilled, and formatted for speed and ease of use.

- **Private contract firefighters** – need information for coordination with public firefighting resources.

- **Federal agencies (e.g., Federal Emergency Management Agency (FEMA), and civil protection organizations)** – need information for deployment of federal assistance, response, and recovery activities.

- **County authorities (e.g., Sheriff, watershed managers)** – need information on the initial start and projected spread of the fire.

- **Local authorities, including law enforcement and transportation departments** – need information on evacuation orders, infrastructure impacts, road closures, train station closures, and airport closures.

- **Utilities** – need start and projected spread information on which to base decisions, e.g., de-energization of the power grid.

- **Risk managers (i.e., individuals responsible for managing facility and institutional risks)** – need information on which to base decisions related to implementation of an emergency response plan, including protection of life safety and preservation of business assets.

- **Public** – needs information related to smoke and emissions, evacuation orders, safety, preservation of personal assets, and receipt of federal assistance.

- **Air quality regulators and public health agencies** – needs information related to smoke and emissions.

3.1.2 Forensic Needs

End users and modeling needs for forensic reconstruction include:

- **Insurers** – need information on which to base legal decisions related to the origin and cause of a fire, parametric rate-of-spread scenarios, and differentiation between the impacts of multiple fire fronts.

- **Accident investigators (e.g., Occupational Safety and Health Administration (OSHA) and California Department of Forestry and Fire Protection (CAL FIRE))** – need information on the origin and cause of a fire, as well as fire behavior, on which to base future loss-avoidance and mitigation actions. Investigators also need information on smoke transport to aid reconstruction studies of smoke impact on evacuation safety and efficiency.

- **Land managers, model developers, and other researchers (e.g., U.S. Forest Service and other forest services, U.S. Department of Interior, universities, research organizations)** – need information on the origin and cause of a fire, as well as fire behavior, for purposes of model validation and quantification of uncertainty. Land managers also need information on smoke transport to aid reconstruction studies of smoke impact on evacuation safety and efficiency.

- **Building code developers** – need information on origin and cause of fire, as well as extent of losses and lessons learned, to be used as a basis for enhanced design provisions intended to reduce potential losses in future wildfire events.

- **Incident commanders/emergency responders** – need information on origin and cause of fire, as well as extent of losses and lessons learned, to be used as a basis to improve future response activities.

- **Public health agencies and researchers** – need smoke information for health associations and quantification.

3.1.3 Planning Needs

End users and modeling needs for planning include:

- **Incident commanders/emergency responders** – need information on fire risk and likely impacts for the purposes of developing emergency response plans, quantifying necessary response and suppression resources, and conducting training scenarios.

- **Federal agencies (e.g., Federal Emergency Management Agency (FEMA) and civil protection organizations)** – need information for planning the deployment of federal assistance, response, and recovery activities.

- **Local authorities (e.g., emergency planners, community planners, building officials)** – need information on fire risk and likely impacts, including the change in risk over time, for the purposes of developing and updating wildfire hazard maps, emergency response plans (including testing of planning and evacuation strategies), land use plans, zoning laws, and building requirements.

- **Utilities** – need information on quantification of fire risk to infrastructure, and management of fuel load.

- **Land managers (e.g., U.S. Forest Service, U.S. Department of Interior, and other forest services)** – need information for evaluation and testing of fuel management strategies.

- **Risk managers (i.e., individuals responsible for managing facility and institutional risks)** – need information on which to base the development of an emergency response plan, including protection of life safety and preservation of business assets.

- **Insurers** – need information on quantification of risk and anticipated losses, vulnerability of structures, and demographics, on which to base portfolio insurance and reinsurance decisions, and setting of premiums.

- **Educators** – need information to educate firefighters on fire spread, local authorities on proper land use, and the public on fire risk, mitigation techniques, and emergency response activities.

- **Public (e.g., property owners, developers, and tenants)** – need information on fire risk and likely impacts, effective mitigation techniques, and emergency response activities, for the purposes of personal preparedness and mitigation of potential losses, as well as protection of life safety and preservation of personal assets.

- **Public health agencies and NGOs** – need information to develop resources, plans, and processes to mitigate smoke impacts.

3.2 Models Currently in Use

A list of fire models currently in use, their applications and uses, including who develops and maintains them, and who the end users are, is provided in Table 3.1.

Table 3.1. List of models currently in use (alphabetical). Developer acronyms are spelled out in Appendix D. Refer to cited documentation for further information on the models.

Model	Developer	Application	Scale[1]	Use	End Users
BEHAVE [30, 31]	USFS	O[2], F[3], P[4]	Regional	Flame spread	USFS and other forest services
BlueSky [3, 32]	USFS	O, F, P	Regional	Smoke transport	USFS
CAWFE [33, 34, 24]	NCAR	O, F, P	Landscape	R[5], PB[6], FM[7], FGF[8],	NCAR, research community
EFFIS [35]	European Commission	O, P	Regional	Risk mapping	Europe
ELMFIRE [36]	REAX Engineering	F, P	Regional	Risk mapping	California Public Utilities Commission
FARSITE [37]	USFS	O, F, P	Regional	ER[9], P, RM[10]	USFS, WIFIRE
FDS [38, 39]	NIST	O[11], F, P	Lab – Community	Research	NIST, USFS, research community
FireFly [40]	CERFACS/UMD	O, F, P	Landscape	Research	CERFACS, University of Maryland
FireFOAM [41, 42]	FM Global	F, P	Lab – Parcel	Research	FM Global, research community
Firemap [43, 44]	UCSD, NSF	O	Regional	Emergency response	Los Angeles Fire Department
FireStar3D [45]	Aix-Marseille Univ.	R	Laboratory	Research	Research community
FIRETEC [46, 47]	LANL	F, P	Parcel – Landscape	R, PB, FM	LANL, USFS, DOD
FlamMap [48]	USFS	O, P	Regional	Fuels management	Land managers
FRPAM [49]	CERN	O, P	Parcel	Emergency response	Emergency responders
FSim [50, 51]	USFS	P	Regional	Risk mapping	USFS, land managers
FSPro [52]	USFS/WFDSS	O, P	Regional	Fire spread probability	Emergency responders, land managers
MesoNH/ForeFire [53, 54]	Università di Corsica	O, F, P	Landscape – Regional	Research	Research community
Near-Term Fire Behavior [55]	USFS/WFDSS	O, F, P	Regional	ER[9], P, RM[10]	USFS, WFDSS
Prometheus [56]	CFS	O	Regional	Fire growth forecasting	Canadian Interagency Forest Fire Centre
Propagator [57, 58]	CIMA	O, F, P	Regional	Risk mapping	Italian civil protection
Spark [59]	CSIRO	O, F, P	Regional	Fire growth forecasting	Australian civil protection
Wildfire Analyst [60]	Technosylva	O	Regional	Fire growth forecasting	California civil protection
WFDS [25, 61]	USFS	O[11], F, P	Lab – Community	R, PB, FM	USFS, research community
WRF-Fire [62, 26]	NCAR	O, F, P	Landscape	Research	Research community, State of Colorado

[1] Length scales: Laboratory (Lab) < Parcel (Stand) < Community < Landscape < Regional
[2] Operational (capable of forecasting)
[3] Forensic
[4] Planning
[5] Research
[6] Prescribed burns
[7] Fuels management
[8] Fire growth forecasting
[9] Emergency response
[10] Risk mapping
[11] Via level set method [63]

4. Research Needs

4.1 Properties of Optimal Models

The ideal properties of optimal large outdoor fire models were discussed in each of the three modeling application areas: Operational, Forensic, and Planning. In most cases, optimal properties were generic across all three modeling application areas. Results are summarized in the sections that follow.

4.1.1 Optimal Properties Across All Models

Optimal properties identified as generic across all types of large outdoor fire models include:

- Efficient, optimized for speed versus complexity
- Capable of modeling fire spread in rural, urban, and suburban landscapes (captures burned area growth)
- Capable of capturing final burned area or "burn scar"
- Captures stochastic nature of fire spread
- Capable of being run as a subsystem for a larger framework
- Utilizes modern computer architectures and flexible enough to run both with and without internet connectivity
- Accurate, reliable, robust, based on state-of-the-art knowledge, capable of utilizing ideal inputs with perfect knowledge of fuel, topography, temperature, weather, and land use
- Software is open source, documented, supported, and peer reviewed, with limitations clearly documented
- Easy to use, easy to interpret, with output that is easily portable to other platforms
- Self-calibrating (i.e., able to utilize machine learning)
- Uncertainties are known
- Utilizes physically measurable inputs and produces physically measurable outputs

4.1.2 Optimal Properties Specific to Operational Models

Optimal properties identified as specific to operational fire forecasting models include:

- Faster than real-time
- Automated
- Ability to predict spot ignitions
- Ability to model fire suppression activities and their influence on fire spread
- Utilizes two-way fire-weather coupling
- Capable of utilizing alternative input sources (e.g., different weather prediction analyses or forecasts)
- Capable of utilizing real-time data on weather, fire location, topography, and fuels
- Capable of producing basic plume structure (e.g., plume height, smoke concentration vs. height)

4.1.3 Optimal Properties Specific to Forensic Models

Optimal properties identified as specific to forensic reconstruction models include:

- High-fidelity and legally admissible in a court of law
- Ability to accurately identify origin of fire and time line
- Ability to identify exactly where ignition occurred in or on each building
- Flexibility to choose algorithms that are more predictive than prescriptive
- Higher level of control over boundary conditions
- Output that is comparable to measured data
- Model results are comparable with different models at overlapping resolution scales

4.1.4 Optimal Properties Specific to Planning Models

Optimal properties identified as specific to planning models include:

- Probabilistic inputs and outputs
- Ability to generate results at appropriate scales (e.g., community, parcel, or landscape scale)

- Ability to couple atmospheric (weather, climate) conditions and allow planning based on weather scenarios
- Capable of testing community planning, evacuation, and fuel management strategies

4.2 Needs Related to Quantification of Uncertainty

Results from large outdoor fire models are inherently uncertain. Limitations in parameterizations and physics representations and incomplete or imperfect knowledge of model inputs (e.g., fuel, topography, weather, and land use) all contribute to modeling uncertainty.

Factors contributing to uncertainty in wildfire modeling were discussed, including consideration of data available for validation, use of expert judgement in modeling, assessment of quality of input and output, and model viability for Monte Carlo simulation or quantification of risk. The following needs related to quantification of uncertainty in model results and available data were identified:

- There is no uniform standard of validation for models; a standard is needed for quantification of uncertainty
- A database of benchmark data is needed for model validation at appropriate scales for the model being tested
- There are significant variations (local and regional) in the completeness and quality of available input data
- There is a lack of adequate data on rate-of-spread because of intermittent measurements
- There is significant uncertainty in how fuel data are characterized
- There is significant uncertainty in atmospheric conditions; parametric variation and ensemble models can be considered
- Quantitative statements of uncertainty on important parameters and available data are needed; uncertainty in input and output data needs to be separated
- More experimental data are needed to quantify important parameters and behaviors (e.g., firebrand generation, lofting, and deposition; ignition of structural assemblies)
- The use of small-scale experiments to validate larger-scale models may not be sufficient (e.g., the relative importance of different heat transfer or flame spread mechanisms may be different at different scales)
- There is a problem with incorporating small scale effects into large-scale properties of a fire and vice versa (i.e., incorporating large-scale weather effects in a model of fine-scale/structural fire behavior); there is an inherent (and poorly understood) separation of deterministic and stochastic processes across the different scales of a wildfire

4.3 Gaps in Large Outdoor Fire Modeling Capabilities

In combination, the three breakout groups generated more than 80 individual gaps suggesting research needs in the areas of input data, physics, model performance, computational resources, expertise in running models, model development, platforms for analyzing results, and institutional support.

Gaps (i.e., research needs) that were identified across all groups were sorted and consolidated into a single list of 22 items for prioritization. The list was reviewed and discussed with the group to confirm that all important ideas were captured. In-person and online participants were then asked to vote for their five (5) highest priority needs. The resulting prioritized list of research needs is provided in Table 4.1.

Table 4.1. Prioritized list of large outdoor fire modeling research needs.

Rank	Research Need Statement	Votes
1	More accurate, more complete, and higher resolution datasets for benchmark validation of wildfire models	●●●●● ●●●● ●● ●●●●●●● ●●● ● ● ●●● (26)
2	Active user communities engaged in maintenance, development, and training for wildfire models	●●●●●●● ●● ●● ●●●● ● ●● ●●●● (22)
3	Fire-weather interaction (weather conditions driving the fire change due to the presence of the fire itself)	●●● ●● ●● ●●●●● ●●● ● ●● ● (19)
4	More certain prediction of long-range firebrand spotting	●●●●●● ●●● ●●●● ●● ● ●● (18)
5	Ability to model structure-to-structure fire spread	●●●●●●●●● ●●●● ●● ●● (17)
6	Next-generation wildfire rate of spread model	●●● ● ● ●●● ●●● ● ● ●●● (16)
7	Quantified uncertainty in measured input and output data	●● ●● ● ● ●● ● ●●● (12)
8	More accurate real-time wildfire data	●●● ●● ● ●● ● ● ● (11)
9	Ability to model effects of response and suppression activities	●●● ● ●● ● (7)
9	Ability to predict heat release rate of complex fuel packages	●● ●● ●●● (7)
9	Ability to run models in the cloud on advanced heterogeneous architectures	● ● ● ●●●● (7)
12	Improved usability	●● ● ● ● ● (6)
12	Simplified smoke plume model	●●●● ● ● (6)
14	Sensitivity study on different modeling considerations	● ● ● ● ● (5)
14	Ability to predict short-range firebrand spotting	●● ● ● ● (5)
16	Ability to model interaction between multiple fires or multiple portions of a single fire	● ●● ● (4)
16	Data management and storage solutions	● ● ●● (4)
18	Fuel pyrolysis and smoldering	● ●● (3)
19	Ability to run models on localized hardware	●● (2)
20	Ability to scale models to spin up quickly	● (1)

- ● High-performance computing
- ● Model user
- ● Experimentalist
- ● Physics-based modeler
- ● Weather / meteorology
- ● Theorist
- ● Responder
- ● Operational modeler

In creating the prioritized list, research needs statements that were closely related were combined into a single statement (e.g., two statements related to structure-to-structure fire spread and two statements related to smoke emissions) and resulting priorities for the combined statements were determined based on a combined tally of votes. Each research needs statement identified in Table 4.1 is described in more detail below:

- **More accurate, more complete, and higher resolution datasets for benchmark**

validation of wildfire models. More accurate, more complete, and higher spatial and temporal resolution data (e.g., fuels, vegetation, terrain, wind and other atmospheric conditions, fire history) are needed for creation of benchmark datasets for validation of wildfire models at parcel, community, and landscape scales.

- **Active user communities engaged in maintenance, development, and training for wildfire models.** Active user communities (in practice and academia), providing a mechanism for communication and feedback between model developers and users, are needed for maintenance and development of wildfire models, and training on proper modeling and use of model results.

- **Fire-weather interaction.** Improved fire-weather interaction modeling through two-way coupling is needed, including an understanding of the conditions for which fire-weather feedback is necessary.

- **Prediction of long-range firebrand spotting.** Long range spotting results in fires that develop independently of the main fire front, potentially reaching a size and intensity that can influence the main fire front's behavior, 1 km to 10 km downwind. Long-range firebrand spotting is random (stochastic) in nature, and difficult to predict and validate. Improved ability to predict and validate long-rage spotting is needed to reduce uncertainty in the prediction of fire behavior.

- **Ability to model structure-to-structure fire spread.** Modeling of structure-to-structure fire spread is still primitive. Improved understanding of the mechanisms contributing to structure-to-structure fire spread, including the ability to account for differences in structure vulnerability to fire, are needed.

- **Next-generation wildfire rate of spread model.** A next-generation fire rate of spread model, including parameterized models for certain physical phenomena (e.g., effects of complex terrain and wind fluctuations), and considering machine learning capabilities, is needed.

- **Quantified uncertainty in measured input parameters and model results.** Quantification of the uncertainty in measured values used for model input parameters and model output are needed to evaluate the accuracy and uncertainty in wildfire models.

- **More accurate real-time wildfire data.** More accurate real-time wildfire data are needed to evaluate and improve wildfire models .

- **Ability to model effects of response and suppression activities.** Improved ability to model the effects of response and suppression activities is needed to increase accuracy in the prediction of fire spread for operational modeling.

- **Ability to predict heat release rate of complex fuel packages.** Improved ability to predict the heat release rate of complex fuel packages (e.g., individual structures and vegetation) is needed.

- **Ability to run models in the cloud on advanced heterogeneous architectures.** The ability to run models in the cloud on advanced heterogeneous architectures could increase computing capacity and reduce computational time.

- **Improved usability.** Improved usability (e.g., user interfaces and effective visualization of results) is needed so that users can obtain the type of data they need in a form that can be understood and effectively used.

- **Simplified smoke plume model.** Simplified smoke plume models (e.g., Gaussian plume models), including smoke yield, radiation and emissions, are needed.

- **Sensitivity study on different modeling considerations.** A study on the sensitivity of model results to different modeling considerations, including uncertainty in input and output parameters, is needed.

- **Ability to predict short-range firebrand spotting.** Short range spotting results in fires that are subsumed in the main fire front, 10 m to 100 m downwind. For sufficiently intense fires, short range spotting has a negligible contribution to the behavior of the main fire front because the spot fires are relatively small (they do not have time to develop). But for lower intensity fires, short range spotting can play a greater role in the behavior of the fireline. Improved ability to predict short-range firebrand spotting (implicit with rate of spread models) is needed to reduce uncertainty in the prediction of fire spread.

- **Ability to model interaction between multiple fires or multiple portions of a single fire.** Interactions between multiple fires, or multiple portions of a single fire, are complex. Improved ability to model interactions is needed to better predict fire spread or determine the origin/cause of a fire.

- **Data management and storage solutions.** At present, results from large fire models challenge mass storage systems, and users may use on in-situ visualization to retrieve data. New data management and storage solutions are needed for the ever-increasing volume of data, and the inevitable need to store more data.

- **Fuel pyrolysis and smoldering.** There is a need for improved thermal degradation models for the multitude of possible vegetation types, including the ability for models to distinguish between dead and live vegetative fuels. Improved subgrid models for drag and heat transfer (both radiative and convective) are subsumed in this need.

- **Ability to run models on localized hardware.** The ability to run certain types of models on local hardware (i.e., on a laptop without an internet connection) is needed for emergency operations in the field where connectivity may be limited. Input/output needs in such cases should require low bandwidth.

- **Ability of physics-based models to scale and spin up quickly.** The ability of physics-based models to scale and spin up quickly on high-performance computing architectures would be needed to enable real-time operational modeling [with physics-base models].

5. Implementation Plans and Grand Challenges

5.1 Problem-Focused Implementation Plans

Based on the prioritized research needs identified in Table 4.1, six of the seven highest priority needs were selected for detailed discussion and development of research plans that could be implemented to solve the need:

- More accurate, more complete, and higher resolution datasets for benchmark validation of wildfire models
- Fire-weather interaction
- More specific prediction of long-range firebrand spotting
- Ability to model structure-to-structure fire spread
- Next-generation wildfire rate of spread model
- Quantified uncertainty in measured input and output data

The remaining high-priority need, entitled "Active user communities engaged in maintenance, development, and training for wildfire models," was considered to be somewhat different from the technical need statements identified above, and was not assigned for further discussion. Although an implementation plan was not developed, this need was considered very important by workshop participants, and is recommended for future consideration along with other high-priority needs.

5.1.1 More Accurate, More Complete, and Higher Resolution Datasets for Benchmark Validation of Wildfire Models

To develop more accurate, more complete, and higher spatial and temporal resolution data (e.g., fuels, vegetation, terrain, wind speed, fire history) for creation of benchmark datasets for validation of wildfire models, the following steps are recommended:

- Define validation concepts and targets. Consider that validation needs should be appropriate for the model scale, and that validation of intermediate modeling steps may be needed, rather than just overall model results.
- Identify what types of data are needed. Examples of necessary environmental data include small-scale laboratory data (e.g., SERDP-funded projects [10]), prescribed burn (e.g., FASMEE [11]), and real fire data (e.g., FIREX-AQ [13]). Specific data needs include better weather data (i.e., not just point data, but spatially-resolved data including fluctuations and influence of turbulence), and more rapid refresh and refinement of fuel characterization (i.e., distribution of trees, and incorporation of remotely sensed data into vertical and horizontal distribution of fuel loads). Also important are

measurements of fire behavior—these include the spread rate along the fire perimeter (not just at the head of the fire), the depth of the fire base all along the fire perimeter, and heat fluxes. Measurements of fire behavior marginal conditions is important for the testing of physics-based models that seek to maximize the physical fidelity of fire behavior predictions. Marginal conditions are relevant to prescribed burning and structure ignition via firebrands, for example. Well constructed experiments are needed that allow a focus on fire behavior in surface fuels, raised fuels, and combinations.

- Conduct a literature review to identify what data exist and determine suitability for use in benchmarking and validation. Examples include laboratory scale tests (e.g., SERDP-funded projects [10]), field tests (e.g., FASMEE [11], RxCADRE [12], FIREX-AQ [13]), and historical events. Possible sources include NIST Building Fire Research Laboratory (BFRL) data from the 1980s, NIST Camp Swift Texas field experiments [64], reconstruction of large fire events in California (REAX Engineering), reconstruction of fire events in Italy (CNVVF and CIMA).

- Define requirements for data quality, and identify systemic errors in input datasets (if they exist).

- Collect and organize available data into a repository. Capture enough data to quantify statistics (e.g., mean, standard deviation, trends, and range of interest) to support sensitivity studies. Identify data sources, document how the data were collected, and whether or not the data were peer reviewed. Consider regional variations in data. There is a need to use the methods and tools of Geospatial Science and Technolgy (GSAT). This is an under-used professional scientific discipline that is critical for well planned and implemented field experiments that result in geospatial data repositories that meet current data quality standards and are accessible for analysis and use with GIS tools. A first step example of data repository that uses ArcGIS Online (AGOL) and a traditional data archive has been implemented for the Camp Swift experiments [64]. An additional example of model and data comparison is provided by the Smoke and Emissions Model Intercomparison Project (SEMIP) [65].

5.1.2 Fire-Weather Interaction

To improve fire-weather interaction modeling through two-way coupling, the following steps are recommended:

- Identify conditions under which fire-weather coupling is necessary and when one- or two-way coupling is needed.

- Recognize that fire-weather interaction is a multi-scale problem and identify the relevant scales. Weather occurs at large scales, and physics-based fire behavior models are at smaller scales.

- Bring together the atmospheric and fire science communities so that each may better understand the what datasets exist, what methodologies exist for collecting data, and where gaps exist in model interaction at overlapping scales.
- Review currently available simple weather models (e.g., DOWNBURST) that could be incorporated into wildfire models.
- Use simple fire plume entrainment principles to create a fire-induced wind field similar to what was done for "nuclear winter" research.
- Test smoke transport with Briggs Plume Rise and Gaussian dispersion.
- Seek to accommodate next-generation weather models.

5.1.3 More Certain Prediction of Long-Range Firebrand Spotting

To improve the ability to predict long-range spotting and reduce uncertainty in the prediction of fire spread, the following steps are recommended:

- Collect and measure more high-resolution[3] data from the field to better understand physical phenomena including: local wind statistics in outdoor environments, the generation of firebrands; geometry and effect of drag laws on transport of firebrands; effect of flaming or smoldering during transport; energy, temperature, and timescale for an firebrands igniting a fire. Utilize satellite and other aerial data, where available.
- Develop physical or empirical models for all processes: ignition, generation, launching, lofting, transporting, and depositing (not just spotting). Note that some processes are more easily defined using first principles (e.g., lofting and launching) and some are not (e.g., ignition and generation).
- Improve treatment of firebrand transport in computational fluid dynamics-based models, including real cases.
- Conduct experiments to quantify firebrand generation and spot fire ignition. In other words, what relationships govern (1) the transition from confined to transported vegetation (firebrand generation) and (2) the ignition of a fuel bed from a burning firebrand (spot fire ignition)?
- Develop probabilistic treatment of firebrand transport in operational models.

[3]In the context of long-range firebrand spotting, data resolution requirements should be commensurate with the large-scale motions in the turbulent boundary layer. Thus, "high resolution" means sampling wind fields at about one-tenth of the boundary layer thickness.

5.1.4 Ability to Model Structure-to-Structure Fire Spread

To improve understanding of the mechanisms contributing to structure-to-structure fire spread, including the ability to account for differences in structure vulnerability to fire, the following steps are recommended:

- Work with industrial partners who are expert in this area.
- Collect data on ignition and subsequent burning for individual structures and communities as a whole and validate local wind statistics in outdoor environments.
- Revisit fuel characterizations and refine definitions for urban areas as fuel.
- Conduct experiments at multiple scales to investigate firebrands, firebrand penetration into structures (e.g., under eves or through exhaust vents), and heat exposure considering:
  - Different building systems and geometries
  - Different building materials
  - Multiple building and community scale effects (e.g., parallel fences; distance between buildings; impact of code provisions)
- Quantify real scale (above wind-tunnel or laboratory scale) firebrand flow and ignition potential and develop capabilities to replicate in the laboratory (including secondary firebrand production).
- Develop loss curves that relate hazard to probability of building loss.
- Expand the CFD models to include community fire spread
- Feed resulting guidance into codes and standards for prevention and mitigation (e.g., required separation between structures for parcel and community planning)

5.1.5 Next-Generation Wildfire Rate of Spread Model

To develop a next-generation fire rate of spread model, including parameterized models for certain physical phenomena (e.g., effects of complex terrain and wind fluctuations), and considering machine learning capabilities, the following steps are recommended:

- Revisit fuel characterizations and refine definitions.
- Improve linkage between weather models and physics-based models. Decide on resolution scale and physics necessary at that resolution scale.
- Evaluate wind impacts on rate of spread through:

- Validation of local wind statistics in outdoor environments (with involvement of the atmospheric science community)
- Parameter sensitivity studies including heating duration and ignition time.
- Consideration of coupled effects between parameters (e.g., cooling effects of wind, heat release rate, turbulence and fanning).

- Connect with computer scientists and explore remote sensing capabilities in support of machine learning.
- Develop sufficient data and metrics for validation of machine learning capabilities. Consider that machine learning is a powerful tool that can be used to fill gaps in available knowledge, but it cannot be used to replace modeling.

5.1.6 Quantified Uncertainty in Measured Input and Output Data

To quantify uncertainty in measured values of input and output data, and to evaluate the accuracy and uncertainty in wildfire models, the following steps are recommended:

- Identify the parameters that most significantly impact model sensitivity.
- Replicate experiments to quantify model uncertainty.
- Develop guidance on how uncertainty should be presented to different audiences.
- Tie uncertainty in modeling input to risk/hazard output, and catalogue how much variation can occur between input and output.
- Compare large scale results to bench scale results to identify which physics and empirical descriptions are relevant at which scale.

5.2 Grand Challenge Research Statements

Highest priority needs and resulting detailed implementation plans were formulated into grand challenge research statements. The resulting list was reviewed and discussed with the group to confirm that all important ideas were captured. In-person and online participants were then asked to vote for their five (5) highest priority statements. The prioritized list of grand challenge research statements is provided in Table 5.1.

Table 5.1. Prioritized grand challenge research statements. Refer to Table 4.1 for voting dot color key.

Rank	Grand Challenge Statement	Votes
1	Develop a modeling framework for predicting generation, lofting, deposition, and ignition from firebrands	●●●●●●●●●● ●●●●●● ●●● ●●●●●●● ●● ●● (30)
2	Develop a predictive system and related cyberinfrastructure for faster than real-time wildfire modeling	●●●●●● ●●● ●● ●●●●● ●● ●●●●● (23)
3	Design a repeatable experiment for structure-to-structure fire spread at parcel to community scale	●●●●●● ●●● ●● ●●● (14)
3	Reconstruct a large loss wildfire event using computational fluid dynamics models	●●● ●●● ● ●●●●● ●● (14)
5	Design measurement techniques to improve instrumentation and measurement of wildfires	●● ●●●● ● ● ●● ● ● (12)
5	Develop the capability to perform automated real-time forecasting of wildfires as soon as they are detected	●●● ● ● ●●● ● ● ●● (12)
7	Develop a wildfire risk assessment framework at the community scale	●●●●●● ●●● ● ● (11)
8	Develop the capability to generate hourly, near-term wildfire risk maps	●●●● ● ● ●● ● ● (10)
9	Identify key parameters influencing uncertainty and quantify the sensitivity of wildfire models to these parameters	●●● ●● ●● ● ● (9)
9	Develop national wildland-urban interface fire hazard and risk maps	●●● ● ●● ●● ● (9)
11	Improve capabilities for determining the area of origin and likely cause of a wildfire	●●● ●● ● (6)
12	Develop a framework for assessing the most applicable model for different fire types and regimes (e.g., under-story, crown, structure-to-structure, wind-driven, smoldering)	● ● ● ● ● (5)
13	Formulate a national organization with the dedicated purpose of public education and awareness on wildfire risk, response, and mitigation	● ● ● ● (4)
14	Utilize a trans-disciplinary approach for leveraging available data for wildfire prediction and prevention	● ● (2)

In creating the prioritized list, grand challenge statements that were closely related were combined into a single statement (e.g., two statements related to firebrand spotting, two statements related to faster than real-time modeling, and two statements related to community resilience) and resulting priorities for the combined statements were determined based on a combined tally of votes. Each grand challenge research statement identified in Table 5-1 is described in more detail below:

- **Develop a modeling framework for predicting generation, lofting, deposition, and ignition from firebrands.** Firebrand spotting is highly uncertain, and improved ability to predict both long-range and short-range firebrand spotting is needed to reduce overall uncertainty in the prediction of fire spread. A modeling framework should be developed that is capable of more accurately predicting the generation, lofting, deposition, and ignition from firebrands, and their contribution to fire spread within communities. An appropriate balance between deterministic and stochastic methods for predicting long-range spotting should be determined.

- **Develop a predictive system and related cyber infrastructure for faster than real-time fire modeling.** A predictive system and related cyber infrastructure should be developed that can make physics-based models run faster than real time, couple these models with next-generation weather models (e.g., [66]), continuously update these models with real-time data using advanced data assimilation techniques, and deliver actionable data and information on fire spread in a form that is appropriate to different user groups.

- **Design a repeatable experiment for structure-to-structure fire spread at parcel to community scale.** Modeling of structure-to-structure fire spread is uncertain, and improved understanding of the mechanisms contributing to structure-to-structure fire spread is needed. A repeatable experiment should be designed at parcel to community scale, and then modeled to identify differences between predicted and actual behavior and to improve predictive capabilities. The experiment should include varying wind speeds and should be able to quantify real scale firebrand flow.

- **Reconstruct a large loss wildfire event using computational fluid dynamics models.** The ability to evaluate and improve wildfire models is an ongoing need. A recent, large loss wildfire event should be selected, all available data collected, and the event reconstructed in as much detail as possible using a computational fluid dynamics (CFD) model. An excellent example of reconstruction at the landscape scale for the 2017 Tubbs fire in California is given by Coen et al. [67]. The goal of this grand challenge is to use meter or sub-meter scale resolution with a physics-based combustion model and a long-range spotting model.

- **Design measurement techniques to improve instrumentation and measurement of wildfires.** In other disasters (e.g., earthquakes, hurricanes, and floods) the geologic and atmospheric conditions associated with the extreme hazard are measured. Conditions associated with wildfires, however, are not adequately measured, if they are measured at all. New measurement techniques are needed to better instrument wildfire events, measure effects in real-time, and collect the data necessary for evaluation of wildfire models.

- **Develop a national computational framework to perform automated real-time forecasting of wildfires as soon as they are detected.** To more rapidly inform response and suppression activities, the capability to automatically detect wildfires and immediately perform real-time forecasting of fire spread is needed for every fire occurring in the United States. Such models should also automatically consider the effects of fire-weather coupling. The concept of this grand challenge is similar to

NOAA's National Hurricane Center [68] and a similar idea in spirit has been previously proposed by Hanson et al. [69].

- **Develop the capability to generate hourly, near-term wildfire risk maps.** Using Monte Carlo simulation of fire size and impacts to assets at risk, the capability of generating hourly, near-term wildfire risk maps for up to seven days is needed. Such simulations must explicitly incorporate uncertainty. Atmospheric scientists would point out that even mesoscale weather model simulations (very coarse for fire applications at 2-10 km) are adequate for 2-3 days. The convective scale weather simulations that are needed for good fire modeling are good for only 1-2 days. The weather models that look out a week (at which they have not much skill) are global models at 25 km or more grid spacing.

- **Identify key parameters influencing uncertainty and quantify the sensitivity of wildfire models to these parameters.** Quantification of uncertainty, in both input and output data, is needed to evaluate the accuracy of wildfire models. Key parameters influencing the calculated effects of wildfires, along with their associated uncertainties, should be systematically identified, and the sensitivity of model results to these parameters should be comprehensively evaluated.

- **Develop national wildland-urban interface fire hazard and risk maps.** In support of planning, prevention, and mitigation activities, national wildland-urban interface (WUI) hazard and risk maps are needed. Such maps should have a shelf-life of at most 10 years, and should be developed considering historic weather conditions of at least 20 years.

- **Develop a wildfire risk assessment framework at the community scale.** A well-structured wildfire risk assessment framework should be developed at the community scale, which identifies the hazard in terms of the frequency of occurrence, explains risk in terms of different possible wildfire outcomes, defines what is considered an acceptable risk for planning and response purposes, and ultimately communicates this information to communities at risk to wildfires.

- **Improve capabilities for determining the area of origin and likely cause of a wildfire.** In support of forensic applications, the ability to successfully identify the area of origin and likely cause of a wildfire, given measurements of fire evolution and response activities, must be improved. This problem falls under the general class of problems called inverse modeling. One brute force and expensive approach to inverse modeling is to run forward models for a range of input parameters and compare the results with observations. Forward mapping using physics-based models would require significant leaps in computational performance.

- **Develop a framework for assessing the most applicable model for different fire types and regimes.** A framework is needed for assessing the applicability of a suite of models for different fire types, such as, under-story fires, crown fires, and structure-to-structure fires. Also, different flame regimes, such as, wind-driven versus smoldering combustion should be considered. The framework should consider uncertainty and should identify the limits of applicability of different models for different purposes.

- **Formulate a national organization with the dedicated purpose of public education and awareness on wildfire risk, response, and mitigation.** In support of operational activities, a national organization should be formulated with a dedicated purpose of considering wildfire hazard and risk, which utilizes results from wildfire modeling to educate the public and increase awareness on wildfire risk, response, and mitigation.

- **Utilize a trans-disciplinary approach for leveraging available data for wildfire prediction and prevention.** A trans-disciplinary approach should be used to leverage available data and information for wildfire prediction and prevention, including turning communities into citizen-scientists, developing typical experimental set-ups with input from modelers, and developing a data repository for integration of data.

6. Summary Recommendations and Conclusions

On March 18-19, 2019, the Fire Research Division of the Engineering Laboratory at NIST held a two-day workshop on Large Outdoor Fire Modeling (LOFM) in Gaithersburg, Maryland. The purpose of this workshop was to assess the state-of-the-art in computational fire modeling and to identify a set of research priorities for driving progress in the development of large outdoor fire models. With more than 50 participants in attendance, and more than 20 additional participants online, more than 80 individual research needs for improvement of large outdoor fire modeling were identified in the areas of input data, physics, model performance, computational resources, expertise in running models, model development, platforms for analyzing results, and institutional support. Workshop participants identified the following highest-priority research needs for large outdoor fire modeling:

- More accurate, more complete, and higher resolution datasets for benchmark validation of wildfire models
- More active user communities engaged in maintenance, development, and training for wildfire models
- Understand fire-weather interactions and dynamics
- More certain prediction of long-range firebrand spotting
- Better ability to model structure-to-structure fire spread
- Develop the next-generation wildfire rate of spread model
- Develop quantified uncertainty in measured input and output data

The highest-priority needs were selected for detailed discussion and development of research plans that could be implemented to solve the need. Highest priority needs and resulting detailed implementation plans were then formulated into grand challenge research statements. Workshop participants then identified the following highest-priority grand challenge research statements for large outdoor fire modeling:

- Develop a modeling framework for predicting generation, lofting, deposition, and ignition from firebrands
- Develop a predictive system and related cyberinfrastructure for faster than real-time wildfire modeling
- Design a repeatable experiment for structure-to-structure fire spread at medium scale
- Reconstruct a large loss wildfire event using computational fluid dynamics models
- Design measurement techniques to improve instrumentation and measurement of wildfires

The resulting research needs, implementation plans, and grand challenge research statements are intended to provide input to NIST in measurement science research efforts to improve large outdoor fire modeling capabilities. The impact of improved models will be to allow stakeholders to better quantify the hazard and risk associated with wildfires and to assist in planning for mitigation of the effects of future wildfires. This information is also intended for use by public and private sector research and development entities with an interest in contributing to the advancement of large outdoor fire modeling capabilities.

Acknowledgments

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Appendix A. Contributors

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Hostikka	Simo	Aalto University	online
Heintz	Jon	Applied Technology Council	in person
Hortacsu	Ayse	Applied Technology Council	in person
Moresco	Justin	Applied Technology Council	in person
Kochanski	Adam	Atmospheric Sciences Dept., University of Utah	in person
Paugam	Ronan	CERFACS	online
Rochoux	Mélanie	CERFACS	online
La Mendola	Saverio	CERN	in person
Rios	Oriol	CERN	in person
D'Andrea	Mirko	CIMA Research Foundation	in person
Fiorucci	Paolo	CIMA Research Foundation	in person
Filippi	Jean-Baptiste Antoine	CNRS/University of Corsica	in person
Mahmoud	Hussam	Colorado State Univeristy	online
Gissi	Emanuele	Corpo Nazionale dei Vigili del Fuoco	in person
Cancelliere	Piergiacomo	Corpo Nazionale dei Vigili del Fuoco	in person
Nochetto	Ricardo	Dept. of Mathematics, University of Maryland	online
Maund	Gavin	Dept. of Fire and Emergency Services	online
Guan	Shanyue	East Carolina University	in person
Wu	Rui	East Carolina University	in person
Dorofeev	Sergey	FM Global	in person
Ditch	Benjamin	FM Global	online
Han	Dong	FM Global	online
Wang	Yi	FM Global	online
Xin	Yibing	FM Global	online
Zeng	Dong	FM Global	online
Balaras	Ilias	George Washington University	in person
Eslami	Mohammadreza	Hinman Consuliting Engineers, Inc.	online
Hedayati	Faraz	Institute for Business and Home Safety	in person
Gorham	Daniel	Institute for Business and Home Safety	in person
Floyd	Jason	Jensen Hughes	in person
Lattimer	Brian	Jensen Hughes	in person
Koo	Eunmo	Los Alamos National Laboratory	in person
Linn	Rodman	Los Alamos National Laboratory	in person
Husted	Bjarne	Lund University	online
Coen	Janice	National Center for Atmospheric Research	in person
Suzuki	Sayaka	National Research Institute of Fire and Disaster	online
Abul-Huda	Yasin	NIST	in person
Bryner	Nelson	NIST	in person
Falkenstein-Smith	Ryan	NIST	in person
Hamins	Anthony	NIST	in person
McDermott	Randall	NIST	in person
Butler	Kathryn	NIST	in person
Manzello	Samuel	NIST	online
Maranghides	Alexander	NIST	in person
McGrattan	Kevin	NIST	in person

Last Name	First Name	Organization	Attendance
Prasad	Kuldeep	NIST	in person
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Schneider	Barry	NIST	in person
Forney	Glenn	NIST	in person
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Lawless	Stephanie	Noblis	online
Zhou	Aixi	North Carolina A&T State University	in person
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Shotorban	Babak	The University of Alabama, Huntsville	online
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Valero	Miguel	Universitat Politècnica de Catalunya	online
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Stanislav	Stoliarov	University of Maryland	in person
Bahrani	Babak	University of North Carolina at Charlotte	in person
Rorabaugh	Daniel	University of Tennessee, Knoxville	in person
Berzins	Martin	University of Utah	in person
Saad	Tony	University of Utah	in person
Chelliah	Harsha	University of Virginia	in person
Larkin	Narasimhan	US Forest Service	online
Liu	Yong	US Forest Service	online
Mell	Ruddy	US Forest Service	online
Moinuddin	Khalid	Victoria University	online
Khan	Nazmul	Victoria Unviersity	online
Simeoni	Albert	Worcester Polytechnic Institute	in person
Rangwala	Ali	Worcester Polytechnic Institute	online

Appendix B. Workshop Agenda

Monday, March 18

8:30 am	Arrival
9:00 am	Welcome
9:15 am	Plenary 1: Chris Lautenberger, REAX Engineering
10:00 am	Plenary 2: Janice Coen, National Center for Atmospheric Research
10:45 am	Plenary 3: Rod Linn, Los Alamos National Laboratory
11:30 am	Lunch
12:30 pm	Breakout Session1: Defining the need for Operational Models, Forensic Reconstruction,Community Planning, Prescribed Burns, Planning Fire Experiments (Operational, Forensic, Planning)
2:00 pm	Coffee break
2:30 pm	Breakout Session 1: Reporting
3:00 pm	Breakout Session 2: Identifying gaps (Operational, Forensic, Planning)
4:45 pm	Reconvene
5:00 pm	Adjourn

Tuesday, March 19

8:30 am	Arrival
9:00 am	Welcome
9:15 am	Breakout Session 2: Reporting
10:00 am	Coffee break
10:15 am	Breakout Session 3: Steps to address the problem (Operational/Forensic/Planning)
12:30 pm	Lunch
1:30 pm	Breakout Session 3: Reporting
2:30 pm	Wrap-up
3:00 pm	Adjourn

Appendix C. Workshop Focus Questions

Ideal Outcomes of the Workshop:

- A clear statement of **why modeling** is a useful tool for understanding the behavior and mitigating the harmful effects of large outdoor fires.
- Development of **grand challenge** problems with a 10 year horizon to focus research efforts.

Fire Modeling Topics:

- Operational Fire Forecasting
- Forensic Reconstruction of Large Outdoor Fire Events
- Planning (Communities, Fuels, Experiments)

Breakout Session 1: Defining the need

1. Define the need of the end user (e.g., incident commander).
2. How can models be helpful in addressing the need? (Why modeling? Do not be constrained by the capabilities of current models.)
3. What models are currently in use? For each model:
   (a) Who develops and maintains the model?
   (b) Who are the users?

Breakout Session 2: Identify gaps

1. List the properties of an optimal model.
2. What are the gaps? (vote)
   (a) Input data (e.g., fuel, weather, terrain, etc.)
   (b) Physics (submodels, coupling scales)
   (c) Model performance (speed, accuracy)
   (d) Computational resources (platforms, architectures, scaling)
   (e) Expertise in running the models
   (f) Platforms for analyzing results (I/O, data science, practical issues, etc.)
3. How do we quantify uncertainty?
   (a) What data is available for model validation?

(b) Is the model viable for Monte Carlo simulations?
(c) Does the model depend on expert user judgment?
(d) How is the quality of the model output assessed?
(e) Is the model viable for risk quantification?
    i. Short-term (3-5 days), e.g., wind events
    ii. Medium-term (seasonal)
    iii. Long-term (climatological)

Appendix D. Acronyms

AGOL	ArcGIS On Line
CAL FIRE	California Department of Forestry and Fire Protection
CAWFE	Coupled Atmosphere-Wildland Fire Environment
CERFACS	Centre Européen de Recherche et de Formation Advancée en Calcul Scientifique
CERN	Conseil Européen pour la Recherche Nucléaire
CFD	Computational Fluid Dynamics
CFS	Canadian Forest Service
CIMA	Centro Internazionale in Monitoraggio Ambientale (CIMA Research Foundation, Italy)
CNVVF	Corpo Nazionale dei Vigili del Fuoco (Italy)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
EFFIS	European Forest Fire Information System
FDS	Fire Dynamics Simulator
FM Global	Factory Mutual Global Insurance Company
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
GSAT	Geospatial Science and Technolgy
LANL	Los Alamos National Laboratory
LOF	Large outdoor fires
LOF&BE	Large Outdoor Fires and the Built Environment
LOFM	Large Outdoor Fire Modeling
NCAR	National Center for Atmospheric Research
NGO	Non-Governmental Organization
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OSHA	Occupational Safety and Health Administration
UCSD	University of California, San Diego
UMD	University of Maryland
USFS	United States Forest Service
WRF	Weather Research and Forecasting model
WFDS	Wildland-urban interface Fire Dynamics Simulator
WFDSS	Wildland Fire Decision Support System
WUI	Wildland-Urban Interface

Appendix E. Plenary Presentation Slides

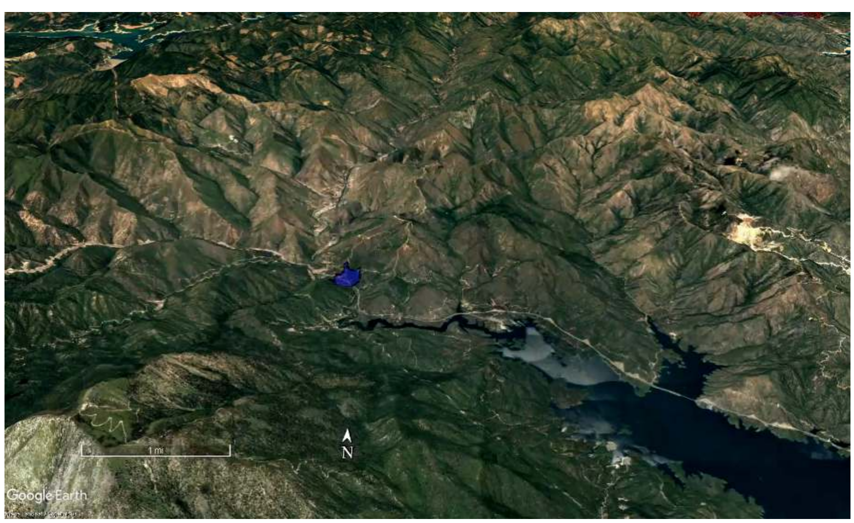
Appendix E.1 Chris Lautenberger (REAX Engineering)

Applications and Limitations of Current-generation 2D Wildfire Models

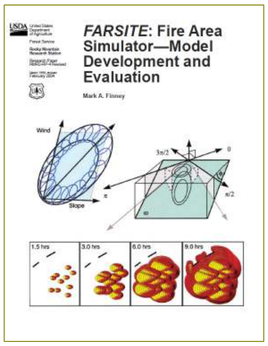
NIST Large Outdoor Fire Modeling Workshop

Chris Lautenberger
March 18, 2019

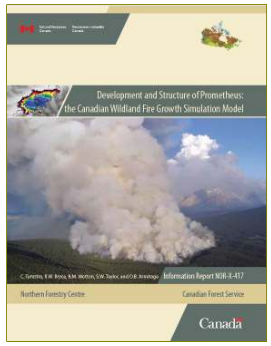
What Are 2D Wildfire Spread Models?



Some 2D Wildfire Spread Models



FARSITE
(US)



Prometheus
(Canada)

Spark
(Australia)

Common Characteristics of Current-Generation 2D Wildfire Spread Models

- Forward rate of spread calculated as a function of surface fuel model, moisture content, topographic slope, and wind speed
  - In the US, this is Rothermel's 1972 equations
- Spread rate in other directions is estimated by assuming that the fire front, under idealized conditions, would take on an elliptical shape
- Semi-empirical submodels for surface spread, crown fire initiation/propagation, and spotting
- No fire/atmosphere coupling or smoke transport

Primary Inputs

Gridded Input Layers

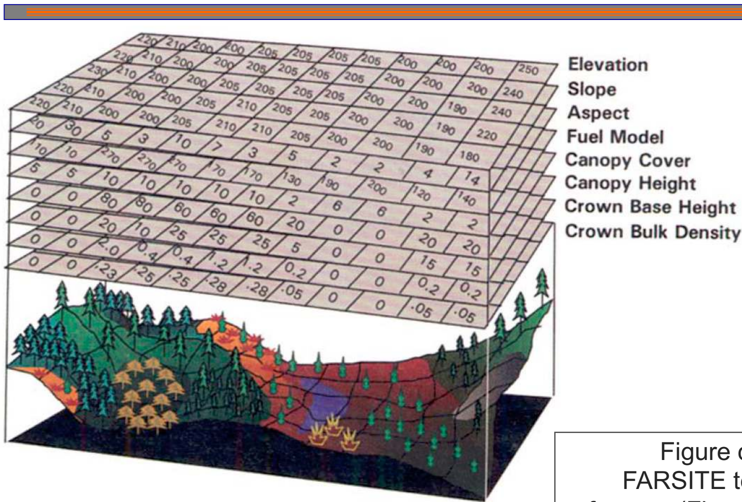
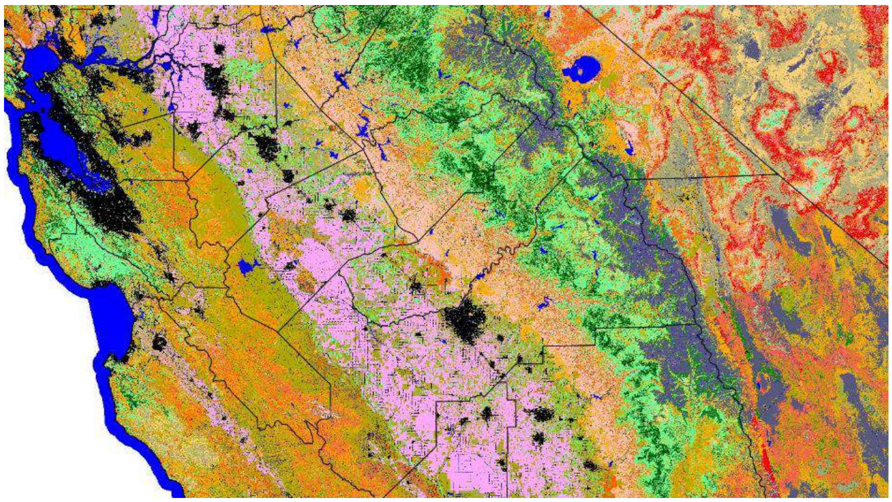
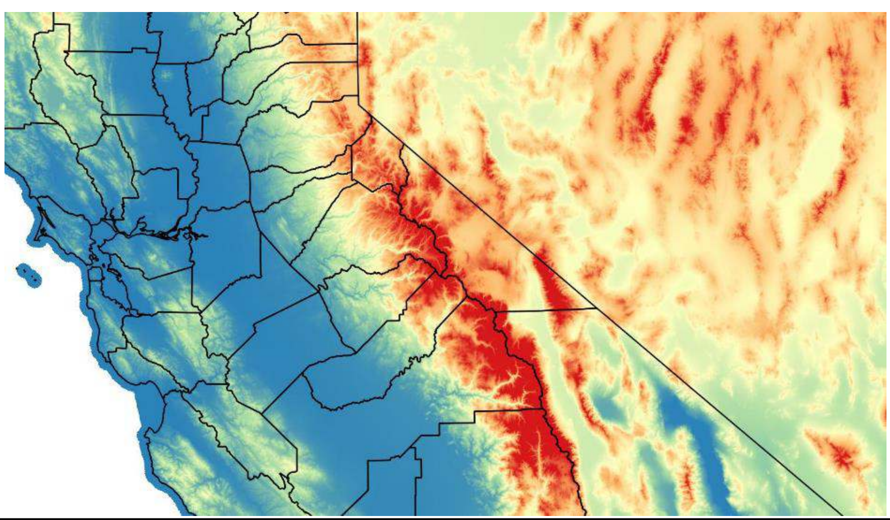


Figure courtesy FARSITE technical reference (Finney 2004)

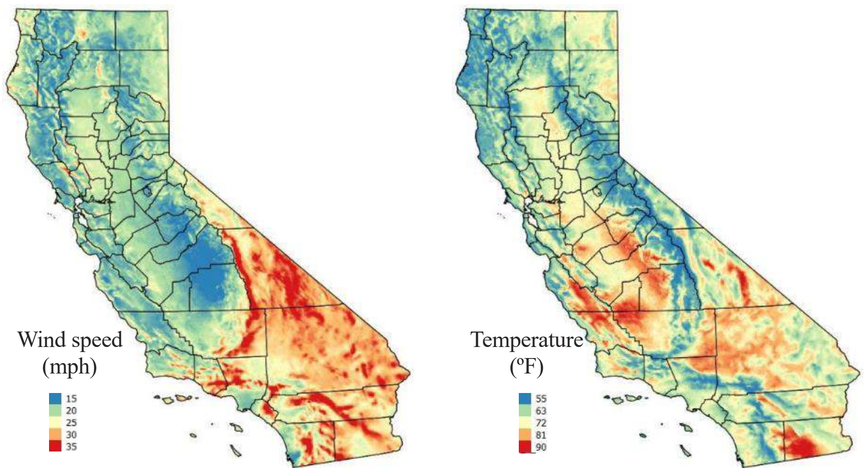
Surface and Canopy Fuels: LANDFIRE



Topography: Elevation, Slope, Aspect



Weather: Gridded Forecast Stream from Numerical Weather Prediction



Applications

What are these models used for?

- Traditional applications
  - Planning fuel treatments – FLAMMAP
  - Suppression planning – FSPRO (WFDSS)
  - Preparedness & response planning – FSim

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  2. Quantifying risk from fire to people & structures for community planning, implementing regulations, etc.
  3. Quantifying short-term fire risk/danger/hazard under antecedent and forecasted weather conditions
  4. Automated real-time forecasting of IA & campaign fires

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ELMFIRE

(Eulerian Level Set Method for Fire Spread)

ELMFIRE: Monte Carlo Wildland Fire Spread Model

- Open source wildland fire spread model
  - http://reaxfire.com/trac/elmfire
- Designed to run on HPC clusters with MPI
- Numerical method after Rehm & McDermott (2009)

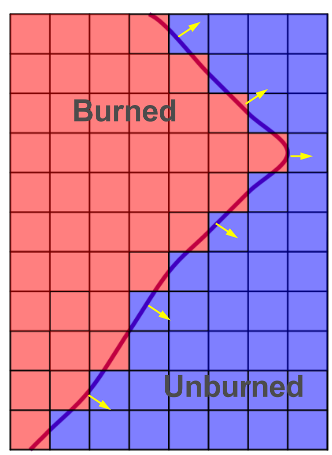
Fire Safety Journal 62 (2013) 289–298
Contents lists available at ScienceDirect
Fire Safety Journal
journal homepage: www.elsevier.com/locate/firesaf

Wildland fire modeling with an Eulerian level set method and automated calibration

Chris Lautenberger*
Reax Engineering Inc., 1921 University Ave. Berkeley, CA 94704, United States

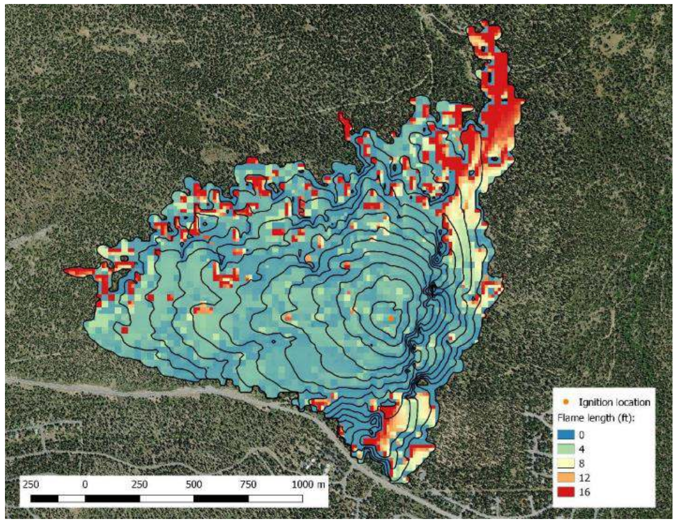
Eulerian Level Set Method

- Eulerian: fixed frame of reference such as a grid
- Level set methods are a class of numerical techniques to track surfaces, shapes, or interfaces
- Track curved surfaces on a grid



Isochrones & Flame Length

REAX ENGINEERING

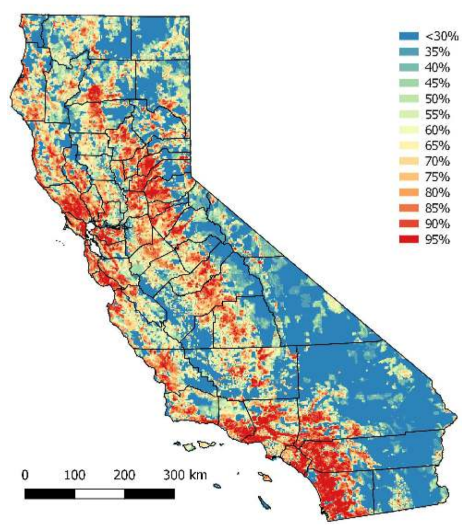


Application: Quantifying risk to structures from fires based on historical weather

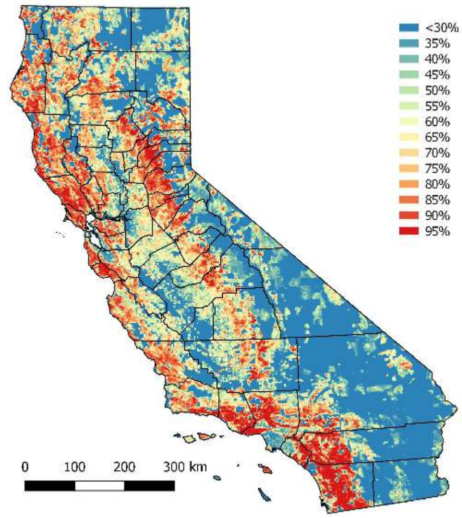
Quantifying Risk of Structure Loss in California

- Step 1: Develop historical fire weather climatology (*e.g.*, using Numerical Weather Prediction)
- Step 2: Monte Carlo fire spread simulation with ignitions distributed randomly across landscape
  - For each ignition location, draw weather stream is drawn randomly from fire weather climatology
  - Simulate fire spread for a duration of several hours
  - Record fire size, average flame length, number of impacted structures, etc. for each ignition location
  - Rinse and repeat: ~100 million simulations for California

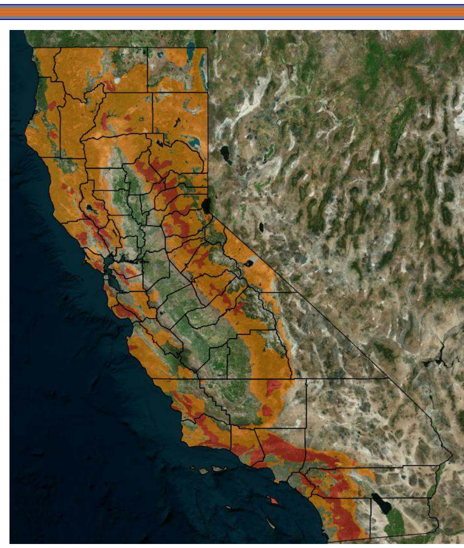
Consequence (Impacted Structures)



Relative Structure Loss Risk



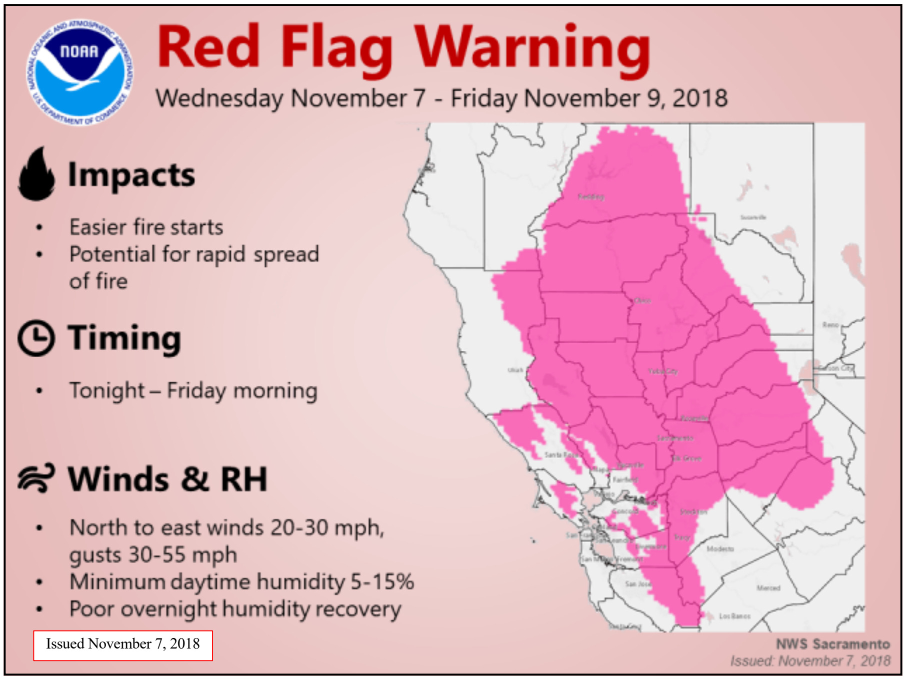
Regulatory Example: CPUC Fire Threat Map



Application: short-term fire danger/hazard/risk forecasting

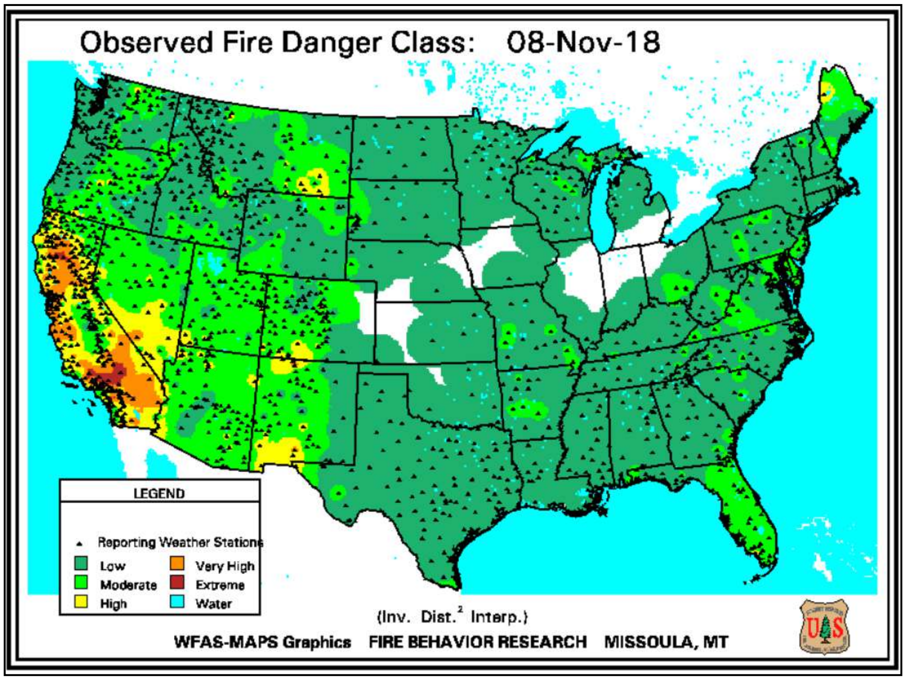
Current Approaches to Quantifying Near-term Fire Danger/Hazard/Risk

- Red Flag Warnings
  - Issued by National Weather Service
  - Meant to be "public facing" – picked up by local TV stations, radio stations, etc.
- National Fire Danger Rating System (NFDRS)
  - Used primarily by fire suppression agencies to stablish staffing levels and daily adjective fire danger ratings
- Both lack spatial and temporal fidelity that may be relevant under extreme weather conditions



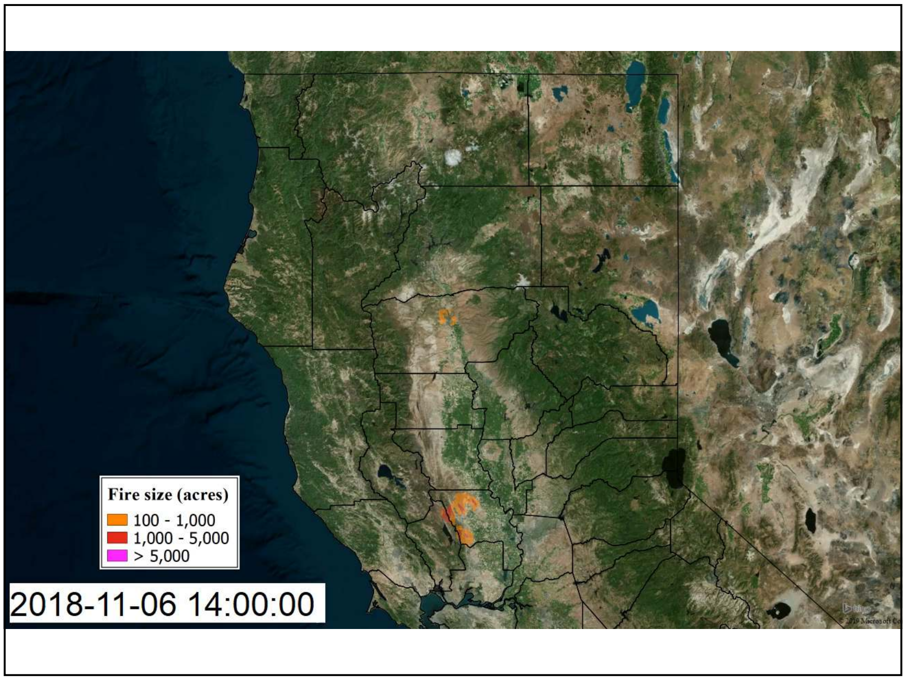
Issued November 7, 2018

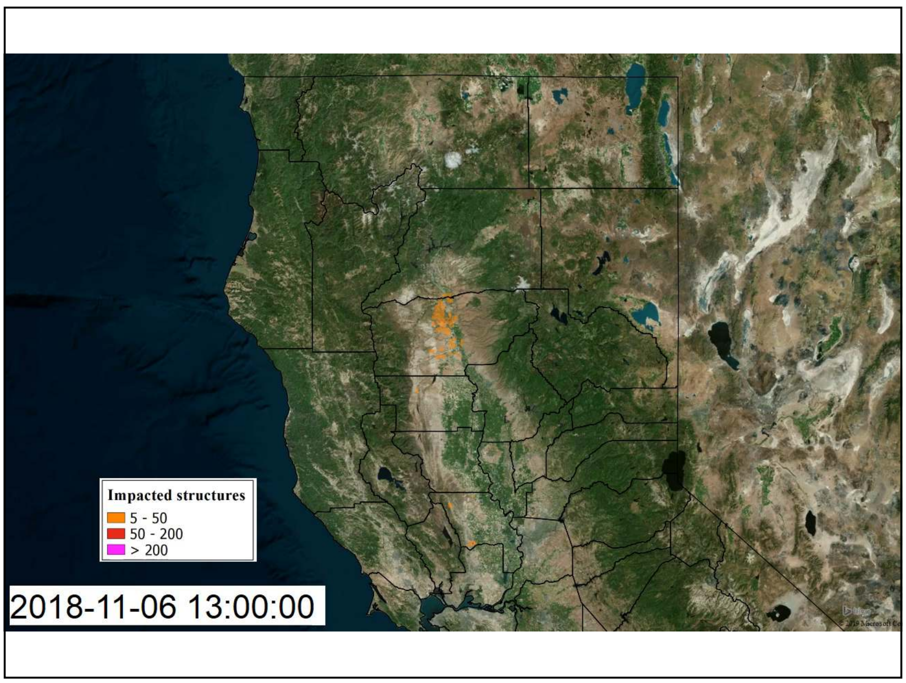
Issued November 8, 2018



Quantifying Near-term Fire Danger/Risk via Fire Modeling

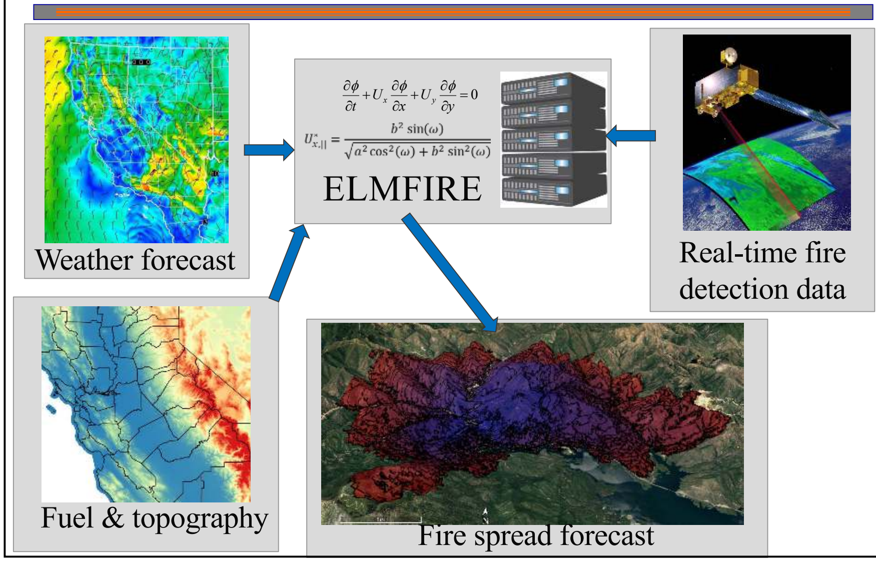
- Basic approach is the same as quantifying fire risk/hazard/danger under historical conditions
  - Model millions of fires ignited in the future at randomized locations under forecasted wind/weather conditions
  - For each combination of ignition location & time of ignition, modeled fire size and # of impacted structures are tabulated
  - Maps with high spatial and temporal fidelity can be generated
- Shown on following slides for 84-hour forecast from November 6, 2018 (two days before Camp Fire)


Fire size (acres)
100 - 1,000
1,000 - 5,000
> 5,000
2018-11-06 14:00:00

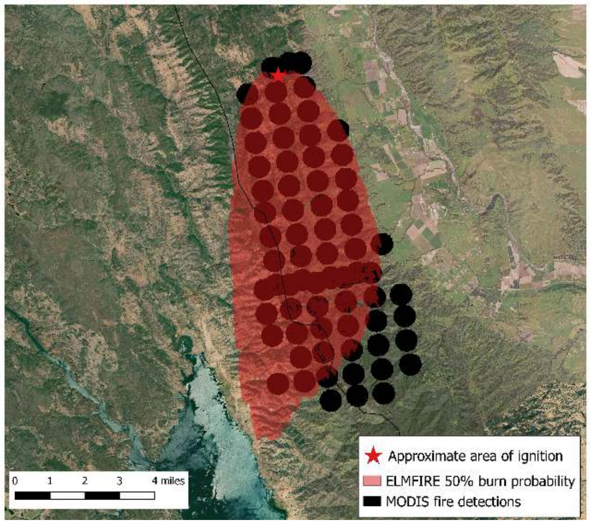

Impacted structures
5 - 50
50 - 200
> 200
2018-11-06 13:00:00

Automated Real-time Fire Forecasting

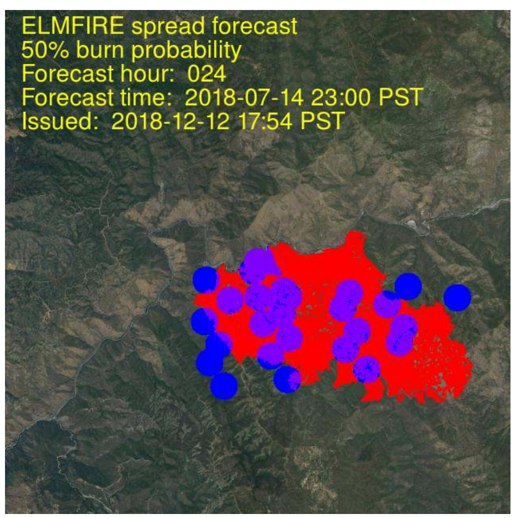
Automated Real-time Fire Forecasting



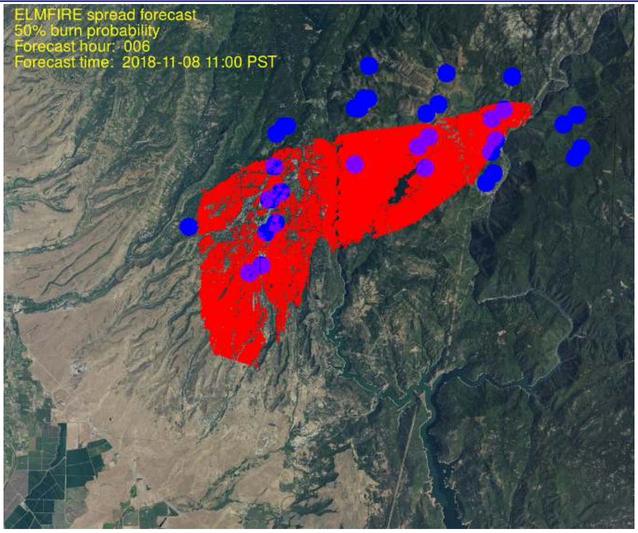
Backtesting & Model Calibration: County Fire



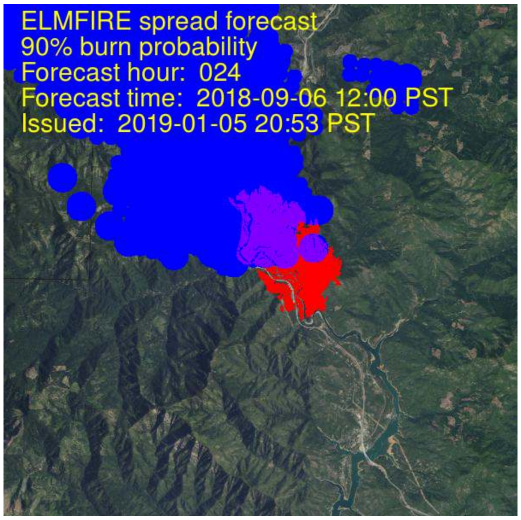
Backtesting & Model Calibration: Ferguson Fire – 24 Hour Forecast



Backtesting & Model Calibration: Camp Fire



Backtesting & Model Calibration: Delta Fire – 24 Hour Forecast



Limitations of Current-generation 2D Wildfire Spread Models

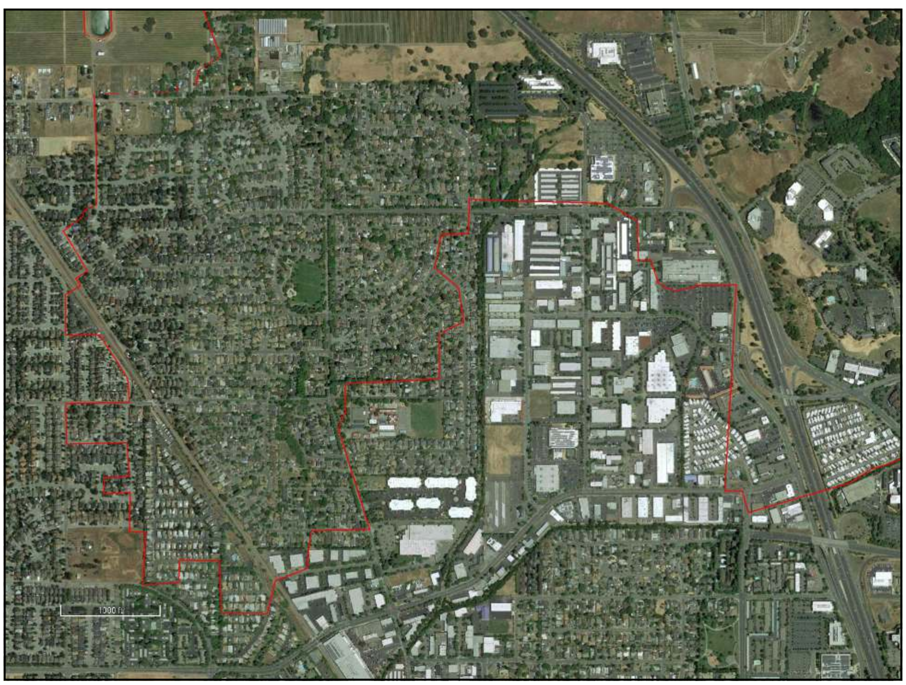
- In a fire modeling context, what are limitations?
  - Things we need to be cognizant of so that we don't misuse models or misinterpret their outputs

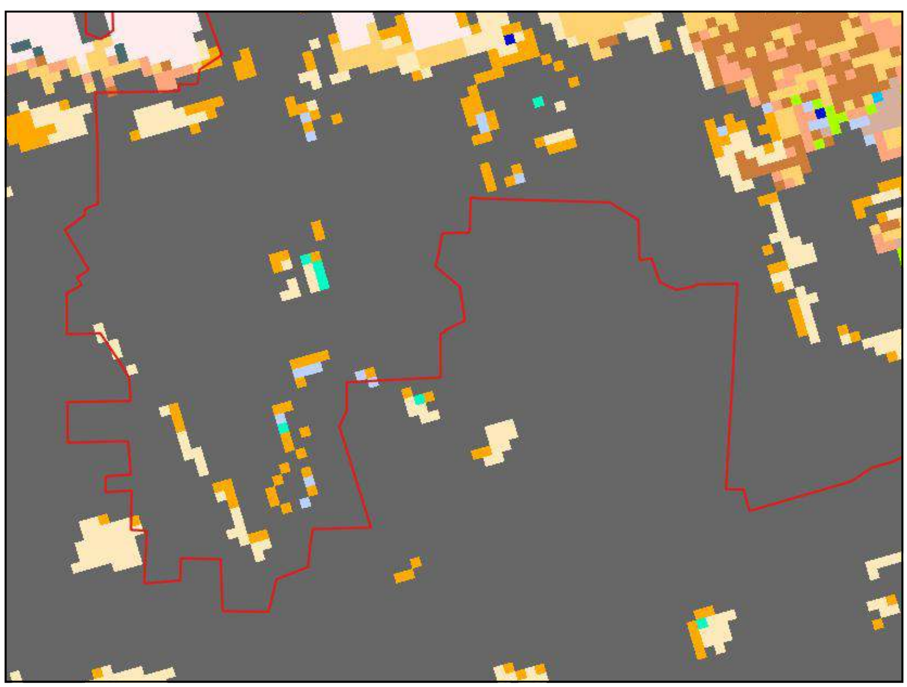
Limitations of Current-generation 2D Wildfire Spread Models

- In a fire modeling context, what are limitations?
  - Things we need to be cognizant of so that we don't misuse models or misinterpret their outputs

But limitations are also opportunities for improvement!

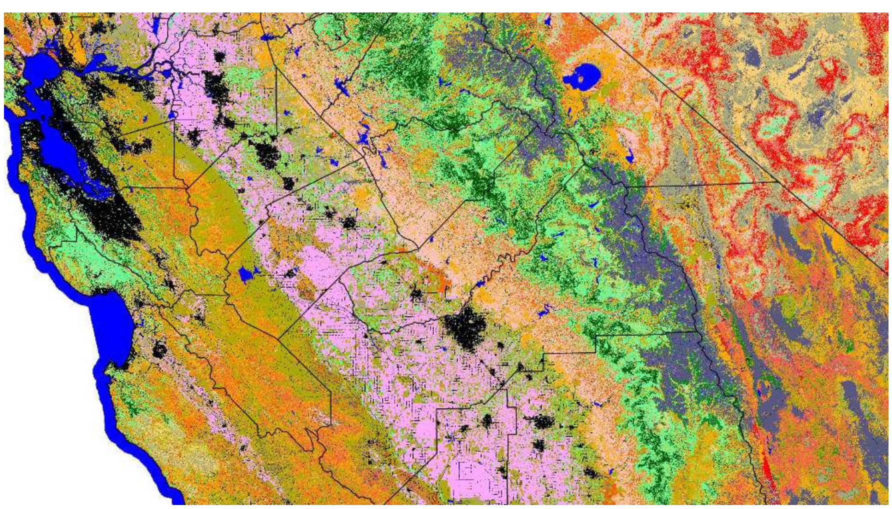
Opportunity for improvement:
Spread in WUI & built up areas





Opportunity for improvement: Fuel inputs

LANDFIRE Fuel Model Assignments



Fuel Model 145 (SH5, High Load Dry Climate Scrub)

Description: The primary carrier of fire in SH5 is woody shrubs and shrub litter. Heavy shrub load, depth 4-6 feet. Spread rate very high; flame length very high. Moisture of extinction is high.

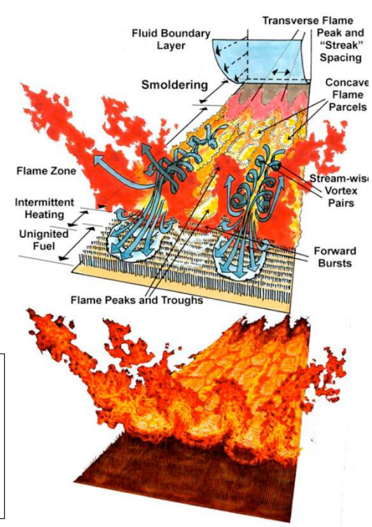
Courtesy Scott and Burgan (2005)

Actual Fuels where LANDFIRE Shows Fuel Model SH5

Opportunity for improvement: surface spread & post-frontal combustion

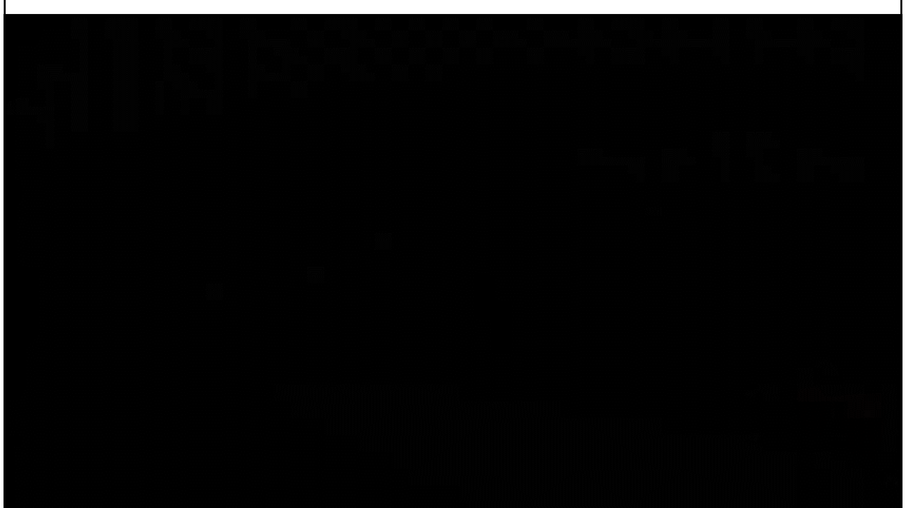
Next Generation Surface Spread Model

- Fundamental understanding of buoyancy-induced flame dynamics and convective heating/cooling of fine fuel particles will lead to next generation models for surface fire spread

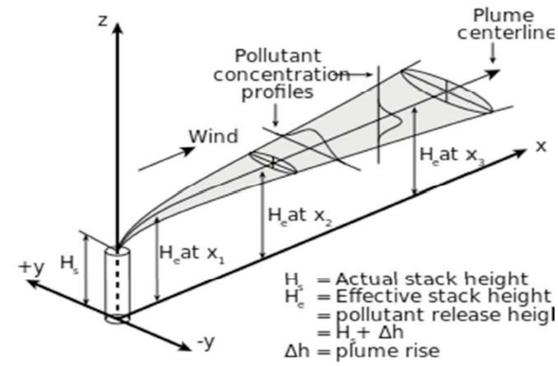


Finney, M.A., Cohen, J.D., Forthofer, J.M., McAllister, S.S., Gollner, M.J., Gorham, D.J., Saito, K., Akafuah, N.K., Adam, B.A, and English, J.D., "Role of buoyant flame dynamics in wildfire spread," *Proceedings of the National Academy of Sciences of the United States of America* **112 (32)**: 9833-9838 (2015).

Opportunity for improvement: Smoke transport & simple fire/atmosphere coupling



Briggs Plume Rise with Gaussian Dispersion



$$C(x,y,z) = \frac{\dot{S}}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z-\Delta h)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+\Delta h)^2}{2\sigma_z^2}\right)\right)$$

Opportunity for improvement: spotting

Spotting

- Can be the dominant mechanism of fire propagation

4-parameter Stochastic Spotting Model

$$m = a \times \dot{Q}'^{b} \times u_{20}^{c}$$

$$v = m \times d$$

$$\mu = ln\left(\frac{m^2}{\sqrt{v + m^2}}\right) \qquad \sigma = \sqrt{ln\left(1 + \frac{v}{m^2}\right)}$$

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{1}{2}\left(\frac{ln\, x - \mu}{\sigma}\right)^2\right)$$

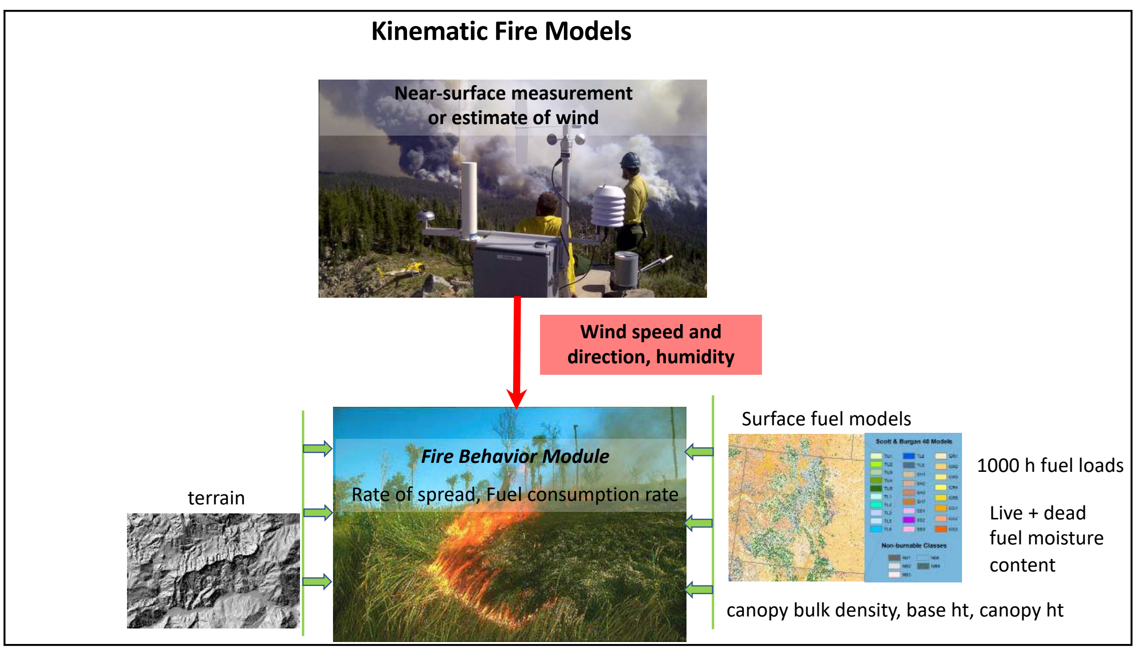
Concluding Remark

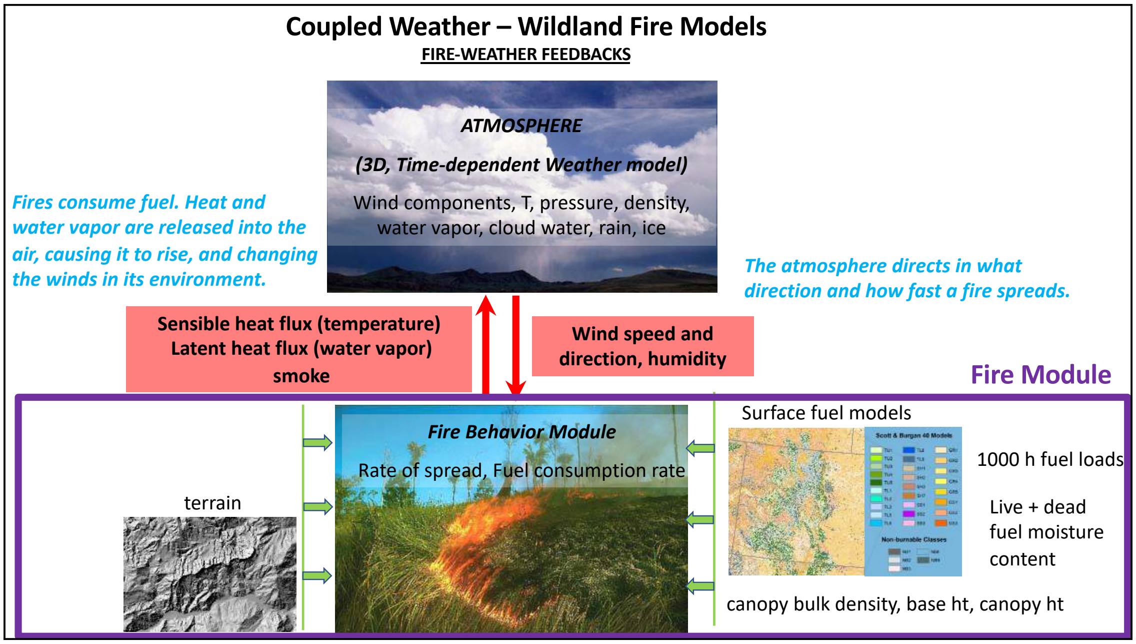
- Howard Emmons once said that the challenge of mathematical modeling is
  - "…not to produce the most comprehensive descriptive model but to produce the simplest possible model that incorporates the major features of the phenomenon of interest."

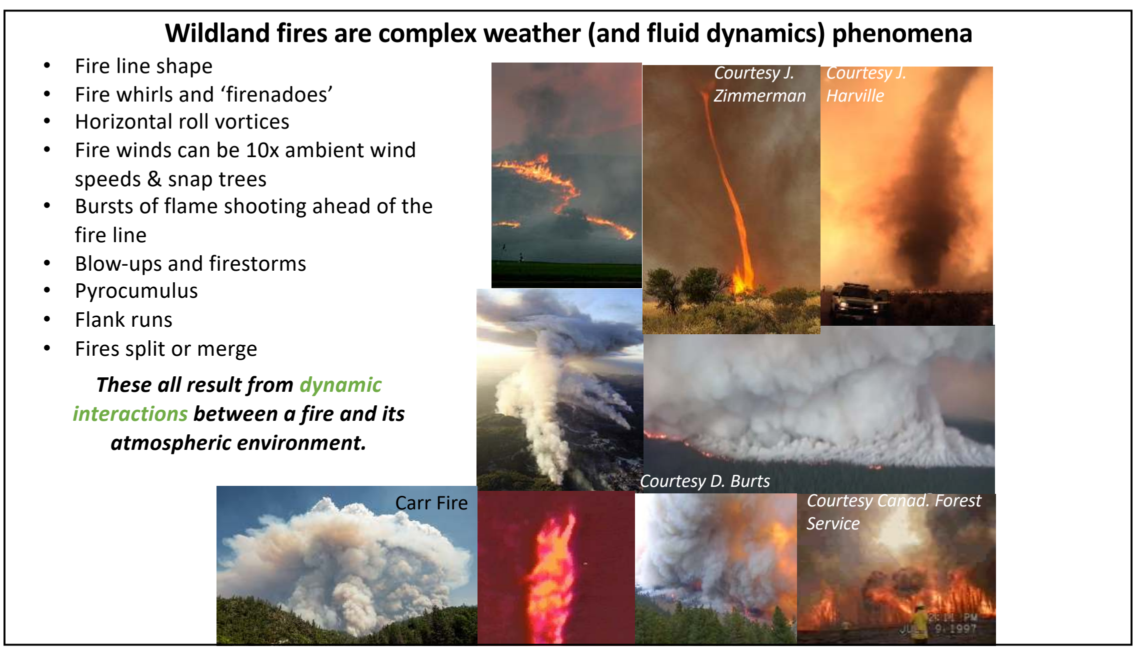
Other Opportunities for Improvement

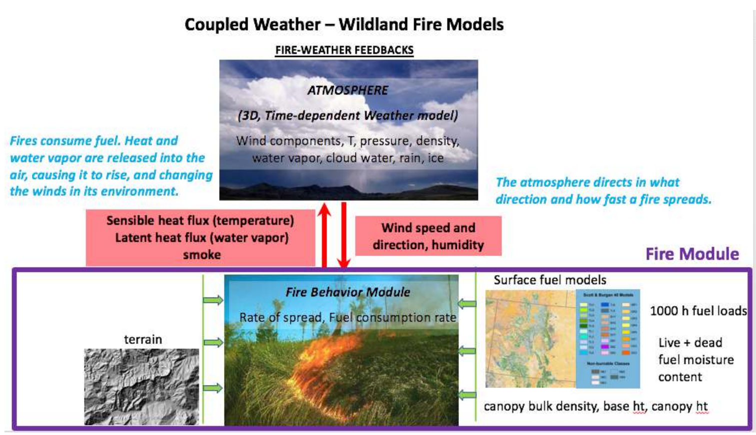
- Upper level winds (spotting) vs. surface winds (fire front propagation)
- Tree mortality & needle accumulation
- Repository for calibration/validation data

Appendix E.2 Janice Coen (NCAR)




Coupled Weather – Wildland Fire Models
FIRE-WEATHER FEEDBACKS
ATMOSPHERE
(3D, Time-dependent Weather model)
Wind components, T, pressure, density, water vapor, cloud water, rain, ice
Fires consume fuel. Heat and water vapor are released into the air, causing it to rise, and changing the winds in its environment.
The atmosphere directs in what direction and how fast a fire spreads.
Sensible heat flux (temperature)
Latent heat flux (water vapor)
smoke
Wind speed and direction, humidity
Fire Module
Fire Behavior Module
Rate of spread, Fuel consumption rate
terrain
Surface fuel models
1000 h fuel loads
Live + dead fuel moisture content
canopy bulk density, base ht, canopy ht


Wildland fires are complex weather (and fluid dynamics) phenomena
• Fire line shape
• Fire whirls and 'firenadoes'
• Horizontal roll vortices
• Fire winds can be 10x ambient wind speeds & snap trees
• Bursts of flame shooting ahead of the fire line
• Blow-ups and firestorms
• Pyrocumulus
• Flank runs
• Fires split or merge
These all result from dynamic interactions between a fire and its atmospheric environment.
Courtesy J. Zimmerman
Courtesy J. Harville
Courtesy D. Burts
Carr Fire
Courtesy Canad. Forest Service



Topics:

What's important (and what is less so)?

What the fire module in a coupled framework can/can't do

Is the weather component doing its job?

Verification – How / Data issues

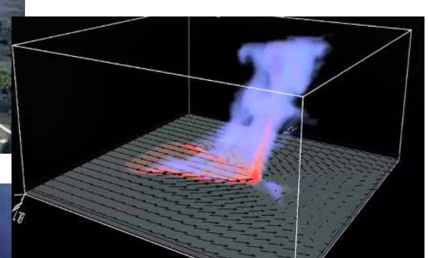
Remaining issues

The CAWFE® model (Coupled Atmosphere-Wildland Fire Environment) couples Numerical Weather Prediction with a wildland fire behavior module

Many fire phenomena arise from weather-fire interactions.

Ex.: the frequently observed elliptical fire front shape and fire whirls

Australian prescribed fire (I. Knight)



CAWFE simulation of a fire in uniform winds (3 m s^{-1} from left) in uniform fuel

The Onion Fire, Owens Valley, CA (C. George)

CAWFE® modeling system (Coupled Atmosphere-Wildland Fire Environment) has two components

a. The Clark-Hall Numerical Weather Prediction Model

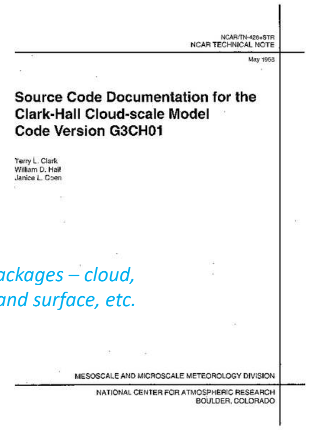
Dynamic core

- 3-dimensional, time dependent
- Nonhydrostatic, anelastic *Solution method*
- Terrain-following coordinates, vertically stretched grid
- Vertical + horizontal grid refinement
- 2-way interacting nested domains
- OpenMP[a] and MPI[b] parallelization

Introduction of wx environment

- Large-scale initialization of atmospheric environment & BCs using gridded analyses or forecast
- Models formation of clouds, rain, ice, and hail in "pyrocumulus" clouds over fires
- Tracks smoke transport
- Aspect-dependent solar heating

Physics packages – cloud, surface, land surface, etc.


NCAR/TN-426+STR
NCAR TECHNICAL NOTE
May 1996

Source Code Documentation for the Clark-Hall Cloud-scale Model Code Version G3CH01

Terry L. Clark
William D. Hall
Janice L. Coen

MESOSCALE AND MICROSCALE METEOROLOGY DIVISION
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

Designed for high-resolution (~ 100s m) simulations in steep, complex terrain.

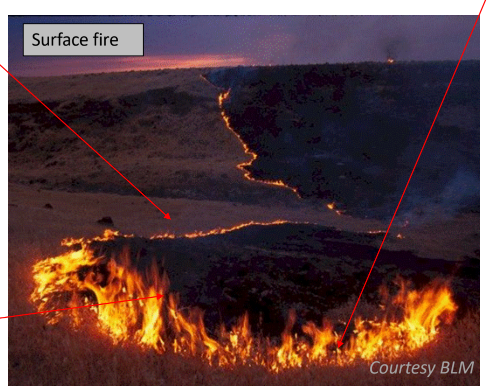
[a] *Clark, Hall, Coen 1996: Source Code Doc. for the Clark-Hall Cloud-scale Model. NCAR Tech Note.*
[b] *Clark et al. 2003: Numerical simulations of grassland fires. J. Geophys. Res.*

b. A Fire Behavior Module

Overview of Components

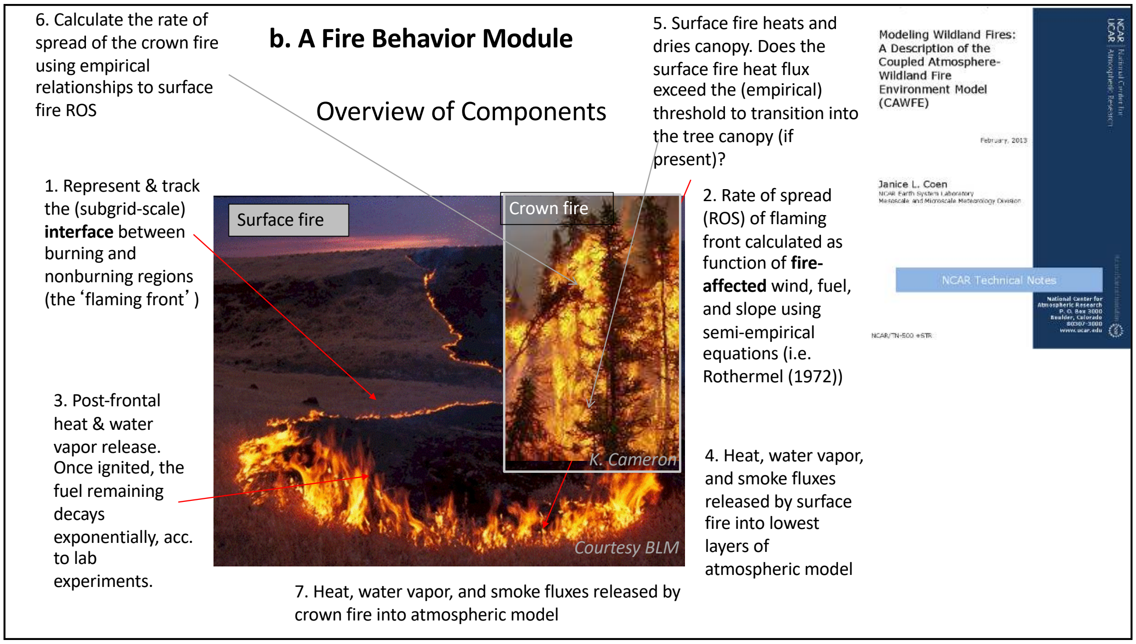
1. Represent & track the (subgrid-scale) the **interface** between burning and nonburning regions (the 'flaming front')

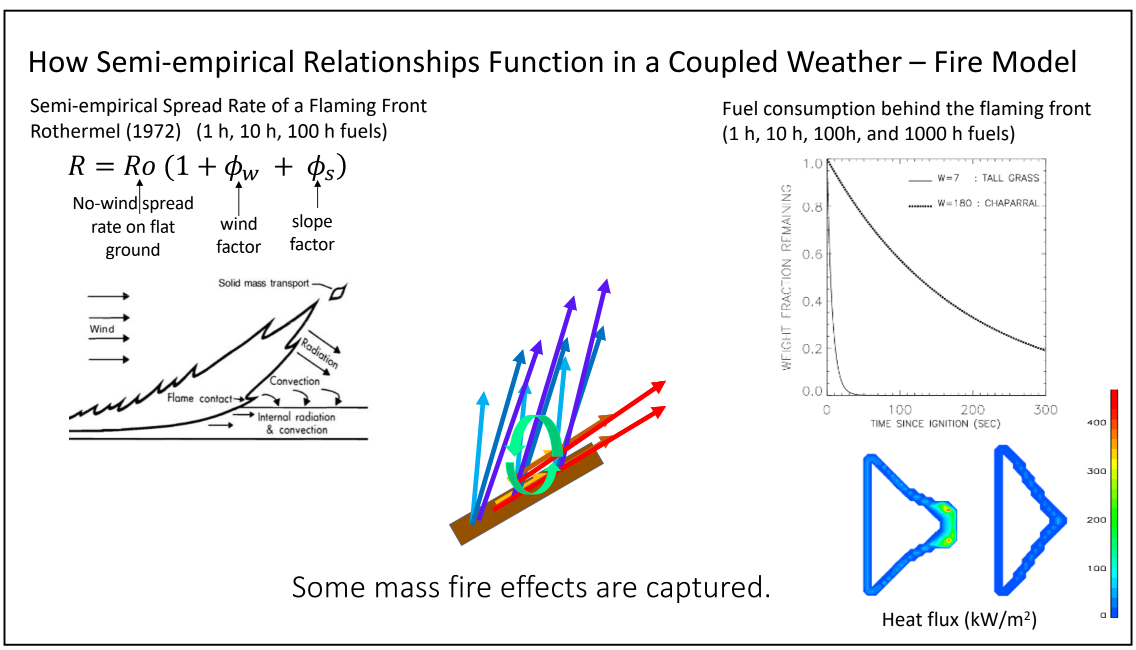
3. Post-frontal heat & water vapor release. Once ignited, the fuel remaining decays exponentially, acc. to lab experiments (BURNUP).

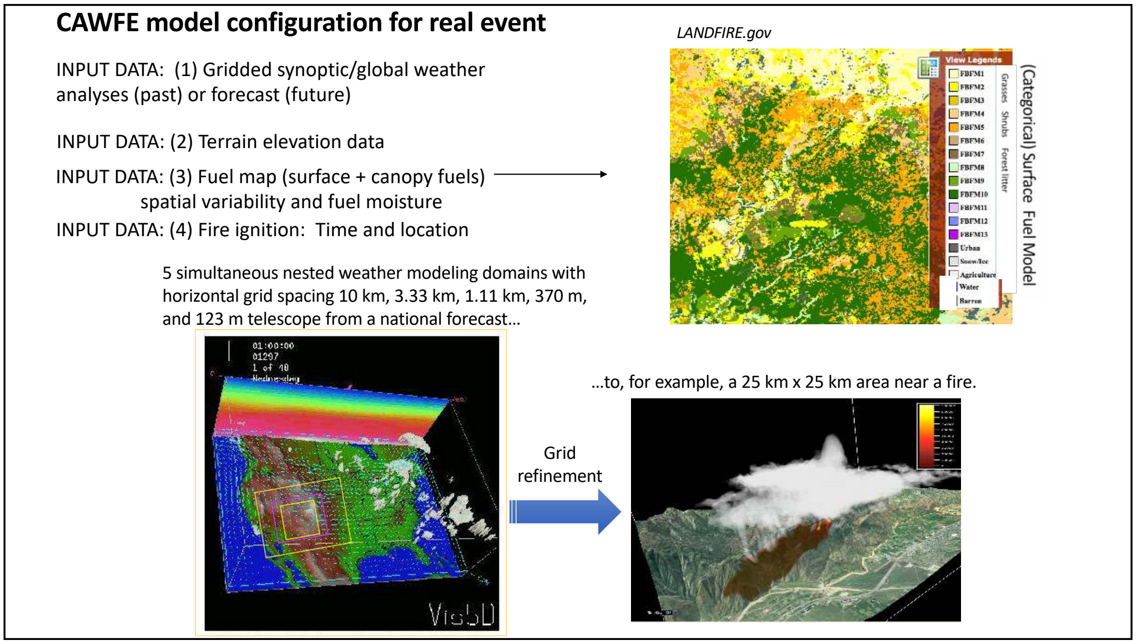


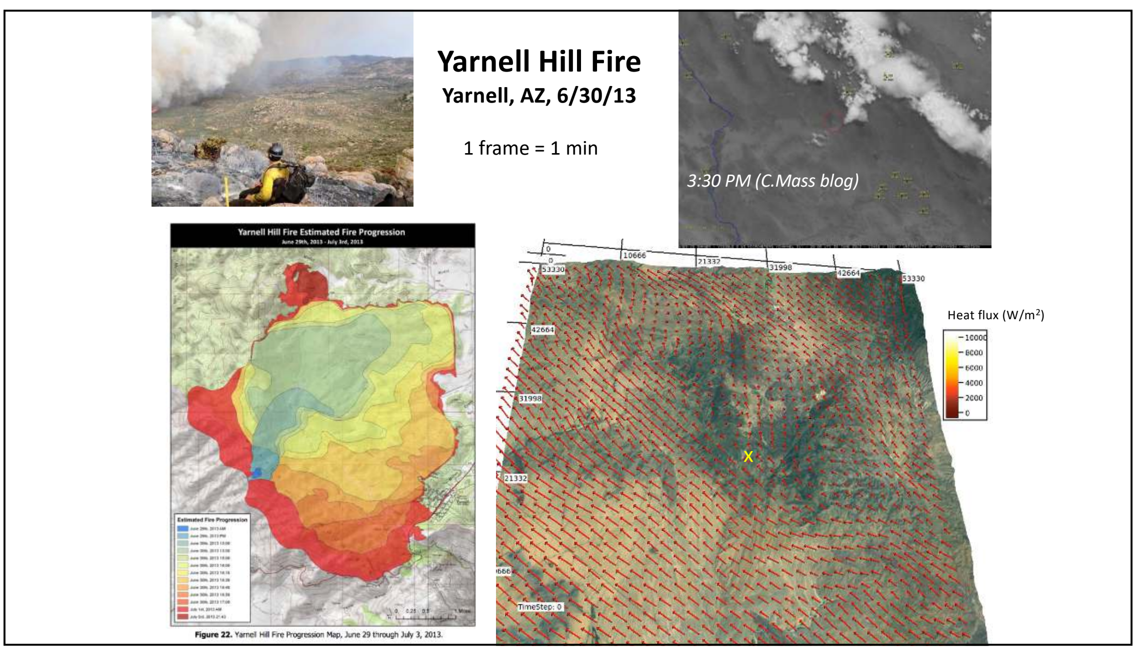
2. Rate of spread (ROS) of flaming front calculated as function of **fire-affected** wind, fuel, and slope using semi-empirical equations (i.e. Rothermel (1972))

4. Heat, water vapor, and smoke fluxes released by surface fire into lowest layers of atmospheric model


b. A Fire Behavior Module
Overview of Components
6. Calculate the rate of spread of the crown fire using empirical relationships to surface fire ROS
1. Represent & track the (subgrid-scale) interface between burning and nonburning regions (the 'flaming front')
Surface fire
Crown fire
K. Cameron
Courtesy BLM
3. Post-frontal heat & water vapor release. Once ignited, the fuel remaining decays exponentially, acc. to lab experiments.
7. Heat, water vapor, and smoke fluxes released by crown fire into atmospheric model
5. Surface fire heats and dries canopy. Does the surface fire heat flux exceed the (empirical) threshold to transition into the tree canopy (if present)?
2. Rate of spread (ROS) of flaming front calculated as function of fire-affected wind, fuel, and slope using semi-empirical equations (i.e. Rothermel (1972))
4. Heat, water vapor, and smoke fluxes released by surface fire into lowest layers of atmospheric model
Modeling Wildland Fires: A Description of the Coupled Atmosphere-Wildland Fire Environment Model (CAWFE)
Janice L. Coen
NCAR Technical Notes


How Semi-empirical Relationships Function in a Coupled Weather – Fire Model
Semi-empirical Spread Rate of a Flaming Front
Rothermel (1972) (1 h, 10 h, 100 h fuels)
$R = Ro\,(1 + \phi_w + \phi_s)$
No-wind spread rate on flat ground
wind factor
slope factor
Solid mass transport
Wind
Radiation
Convection
Flame contact
Internal radiation & convection
Fuel consumption behind the flaming front
(1 h, 10 h, 100h, and 1000 h fuels)
W=7 : TALL GRASS
W=180 : CHAPARRAL
WEIGHT FRACTION REMAINING
TIME SINCE IGNITION (SEC)
Some mass fire effects are captured.
Heat flux (kW/m²)


CAWFE model configuration for real event
INPUT DATA: (1) Gridded synoptic/global weather analyses (past) or forecast (future)
INPUT DATA: (2) Terrain elevation data
INPUT DATA: (3) Fuel map (surface + canopy fuels) spatial variability and fuel moisture
INPUT DATA: (4) Fire ignition: Time and location
5 simultaneous nested weather modeling domains with horizontal grid spacing 10 km, 3.33 km, 1.11 km, 370 m, and 123 m telescope from a national forecast…
LANDFIRE.gov
(Categorical) Surface Fuel Model
Grasses
Shrubs
Forest litter
View Legends
Grid refinement
…to, for example, a 25 km x 25 km area near a fire.
VisSD


Yarnell Hill Fire
Yarnell, AZ, 6/30/13
1 frame = 1 min
3:30 PM (C.Mass blog)
Yarnell Hill Fire Estimated Fire Progression
Estimated Fire Progression
Figure 22. Yarnell Hill Fire Progression Map, June 29 through July 3, 2013.
Heat flux (W/m²)
10000
8000
6000
4000
2000
0
TimeStep: 0

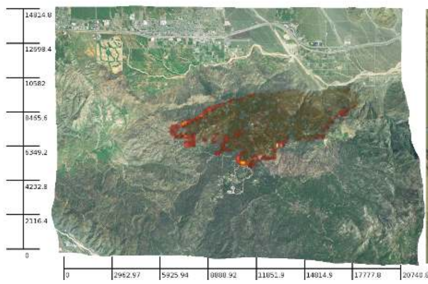
Testing and Verification Cases

Simulated large wildfires in many fuel & weather conditions:

- 2012 Little Bear Fire, NM
- 2012 High Park Fire, CO
- 2006 Esperanza Fire, CA
- 2013 Canyon Creek, OR
- 2007 Witch Fire, CA
- Prototype real-time simulation of CO fires during 2004
- 2003 Simi Fire, CA
- 2002 Troy Fire, CA
- 2000 Spade Fire, MT
- 2016 Tubbs Fire, CA
- 2017 Thomas Fire, CA
- 2002 Big Elk Fire, CO
- 2002 Hayman Fire, CO
- 2013 Yarnell Hill Fire, AZ
- 2014 King Fire, CA
- 2017 Redwood Valley Fire, CA
- 2018 Camp Fire, CA

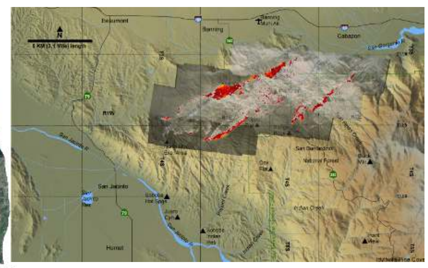
ESPERANZA WILDFIRE

CAWFE SIMULATION



INFRARED DATA

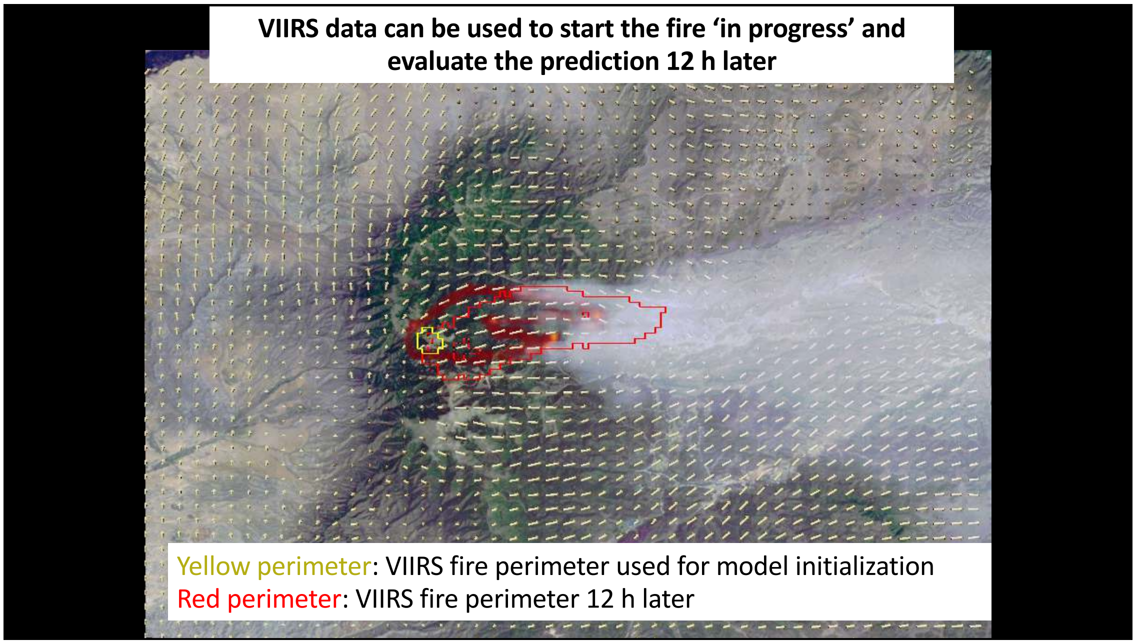
FireMapper, USDA Forest Service

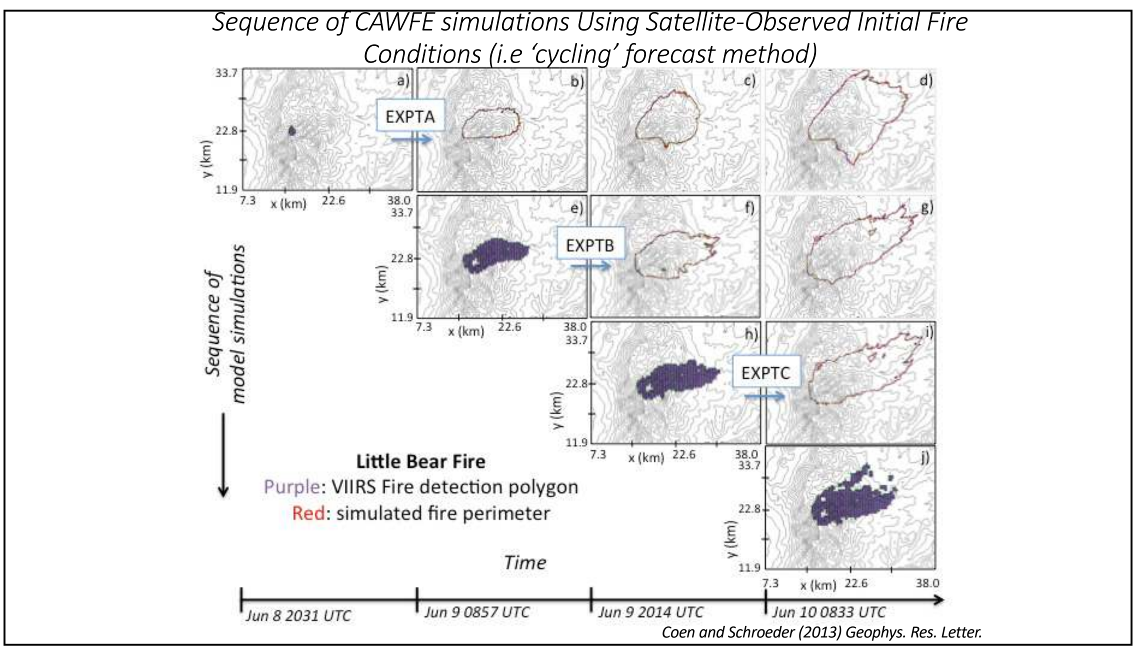


Landscape-scale approach: *Modeled weather, fire extent, shape, intensity, and some land surface effects (severity) May be documentation of phenomena. Airborne or space borne infrared data reveal fire properties through smoke.*

Wildland fires as a weather forecasting problem:

- Following a lightning strike, a fire may
  - smolder for several days without growing, until dry, windy weather occurs and experience lulls for several days in between growth periods
  - continue for weeks or months.
- Weather forecast skill deteriorates with time, particularly small features
  - A forecast initialized at ignition would lose most of its accuracy by the time of fire growth.
  - A single forecast cannot cover a fire's lifetime accurately.
- Models cannot foresee everything:
  - Firefighting could be affecting fire growth
  - Unpredictable processes such as spotting could create new fires


VIIRS data can be used to start the fire 'in progress' and evaluate the prediction 12 h later
Yellow perimeter: VIIRS fire perimeter used for model initialization
Red perimeter: VIIRS fire perimeter 12 h later


Sequence of CAWFE simulations Using Satellite-Observed Initial Fire Conditions (i.e 'cycling' forecast method)
EXPTA
EXPTB
EXPTC
Sequence of model simulations
Little Bear Fire
Purple: VIIRS Fire detection polygon
Red: simulated fire perimeter
Time
Jun 8 2031 UTC
Jun 9 0857 UTC
Jun 9 2014 UTC
Jun 10 0833 UTC
Coen and Schroeder (2013) Geophys. Res. Letter.

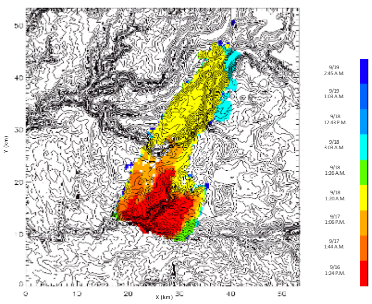
Where this work brought us….

- Wildfire events are (mostly) understandable and model-able.
  - CAWFE case studies showed that if fine-scale (~few hundred meter grid spacing) atmospheric motions are resolved and fire-induced winds are represented, events and phenomena can be reproduced.
- Many aspects of large wildfires are predictable.
  - Using VIIRS active fire detection data to initialize fire extent 'in progress' in CAWFE allows an accurate fire growth prediction for next 12-24 h
  - Given regular observations, can maintain skill long enough to reach next VIIRS observation
  - Applied as a cyclical forecast, allows prediction of fire growth from first detection to extinction

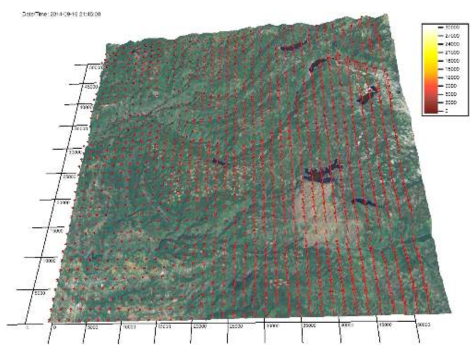
The 2014 King Megafire (Sierra Nevada Mountains)

Though widely attributed to drought and fuel accumulation, the King Fire owed its unanticipated rapid growth to (1) microscale circulations within the Rubicon Canyon and (2) fire-induced winds.

2014 King Fire VIIRS IR fire maps

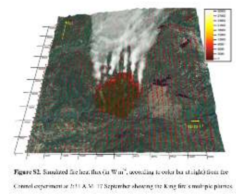


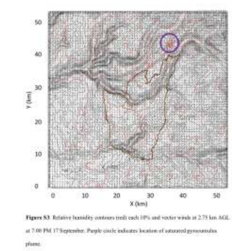
CAWFE simulation
9/16/14 9:45 pm – 9/18/14 10:45 am (37 hr)



Other features:

Multiple plumes





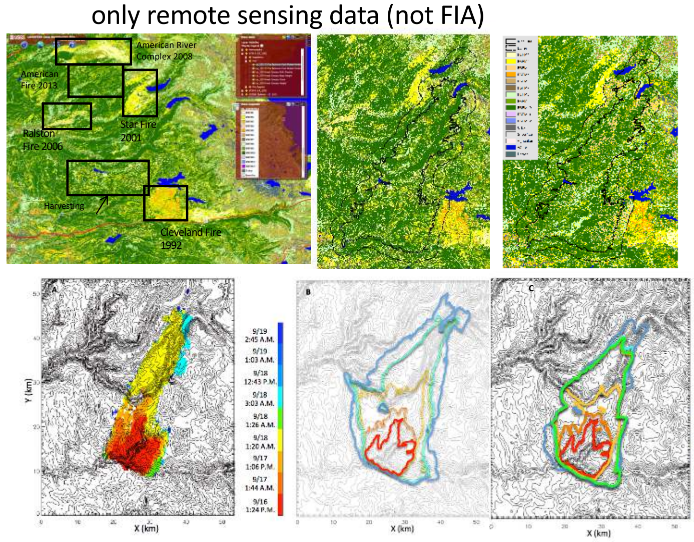
PyroCu at top of canyon

Coen, J. L., E. N. Stavros, and J. Fites-Kaufman, 2018: Deconstructing the King megafire. Ecol. Applic. doi:10.1002/eap.1752.

First, improve (categorical) fuel model mapping (classification), using only remote sensing data (not FIA)

Remotely sensed fuel properties impacted CAWFE simulations of King Fire behavior, particularly in disturbed areas

Stavros, Coen, Peterson, Singh, Kennedy, Ramirez, Schimel, 2018. Rem. Sens. App.: Soc. & Env.



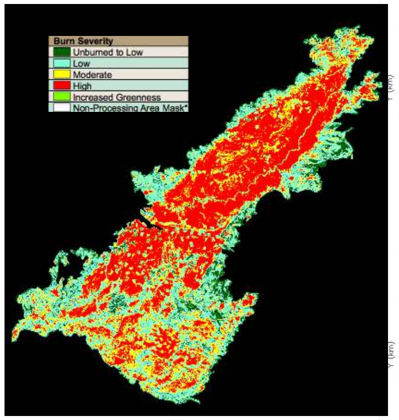
VIIRS (active fire detection data)

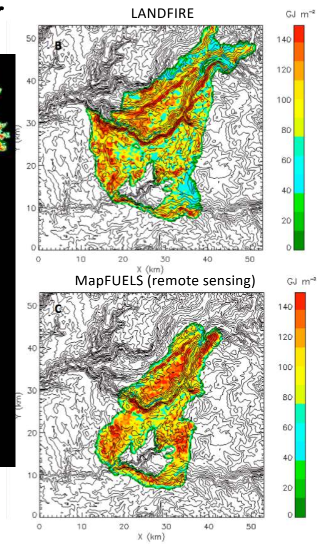
CAWFE simulation using LANDFIRE-based fuel models

CAWFE simulation using MAPFuels fuel models

Simultaneously, remotely sensed fuels improved simulated severity

Rapid Assessment of Vegetation Condition after Wildfire (RAVG) Composite Burn Index

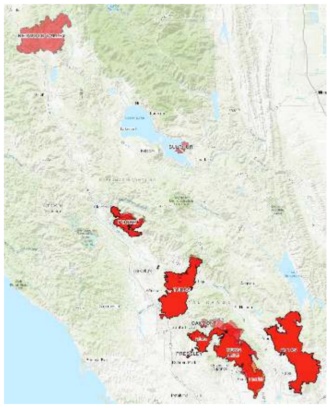




Coen, J. L., E. N. Stavros, and J. Fites-Kaufman, 2018: Deconstructing the King megafire. Ecol. Applic. doi:10.1002/eap.1752.

Tubbs Fire. Photo courtesy San Francisco Herald

October 8-9, 2017 North Bay Wildfires



Top 20 Most Destructive California Wildfires (As of November 2018)

	FIRE NAME *(CAUSE)*	DATE	COUNTY	ACRES	*STRUCTURES*	DEATHS
1*	Camp Fire *(Under Investigation)*	November 2018	Butte County	153,336	18,804	85
2	TUBBS *(Under Investigation)*	October 2017	Napa & Sonoma	36,807	5,636	22
3	TUNNEL - Oakland Hills *(Rekindle)*	October 1991	Alameda	1,600	2,900	25
4	CEDAR *(Human Related)*	October 2003	San Diego	273,246	2,820	15
5	VALLEY *(Electrical)*	September 2015	Lake, Napa & Sonoma	76,067	1,955	4
6	WITCH *(Powerlines)*	October 2007	San Diego	197,990	1,650	2
7	CARR *(Human Related)*	July 2018	Shasta County, Trinity County	229,651	1,604	8
8	NUNS *(Under Investigation)*	October 2017	Sonoma	54,382	1,355	3
9	THOMAS *(Under Investigation)*	December 2017	Ventura & Santa Barbara	281,893	1,063	2
10	OLD *(Human Related)*	October 2003	San Bernardino	91,281	1,003	6
11	JONES *(Undetermined)*	October 1999	Shasta	26,200	954	1
12	BUTTE *(Powerlines)*	September 2015	Amador & Calaveras	70,868	921	2
13	ATLAS *(Under Investigation)*	October 2017	Napa & Solano	51,624	783	6
14	PAINT *(Arson)*	June 1990	Santa Barbara	4,900	641	1
15	FOUNTAIN *(Arson)*	August 1992	Shasta	63,960	636	0
16	SAYRE *(Misc.)*	November 2008	Los Angeles	11,262	604	0
17	CITY OF BERKELEY *(Powerlines)*	September 1923	Alameda	130	584	0
18	HARRIS *(Under Investigation)*	October 2007	San Diego	90,440	548	8
19	REDWOOD VALLEY *(Under Investigation)*	October 2017	Mendocino	36,523	546	9
20	BEL AIR *(Undetermined)*	November 1961	Los Angeles	6,090	484	0

Occurred during Oct. 8-9 event

***This list does not include fire jurisdiction. These are the Top 20 regardless of whether they were state, federal, or local responsibility. 12/4/2018

- On Oct. 8-9, > 170 wildfires ignited in the Wine Country, northern coastal ranges, and Butte and Nevada Counties to the west, north, and east of CA's northern Sacramento Valley.
- Of these, 14 large fires grew rapidly, some joining into multi-fire complexes.
- Investigative reports determined several were started by electrical equipment, in some cases by branches being brought into contact with electrical equipment.
- Many appeared and rapidly spread during local peaks of an unusually strong downslope wind event.

The October 8-9, 2017, North Bay wildfires occurred during a regional wind event

- "Diablo Winds" (Jan Null)
- Bay area meteorological phenomenon similar to Santa Anas
  - Strong high pressure over Great Basin and lower pressure offshore SF and Monterey
  - Characterized by low RH and high wind speeds
- Diablo winds were associated with Oakland Hills fire (Oct. 1991)
- An indication of the strength is given by the inland – offshore pressure gradient

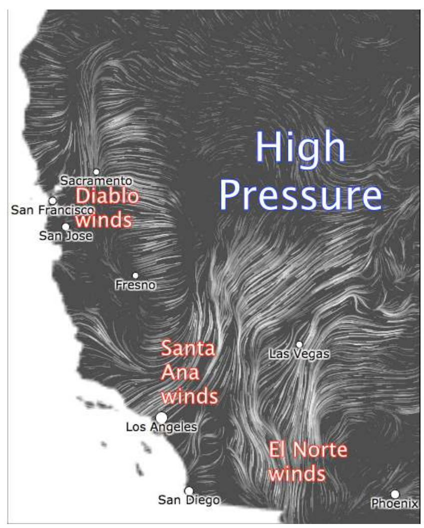
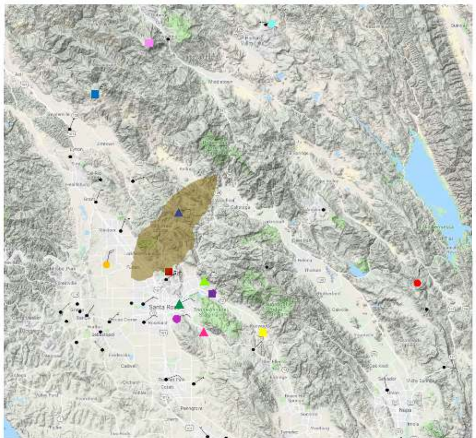
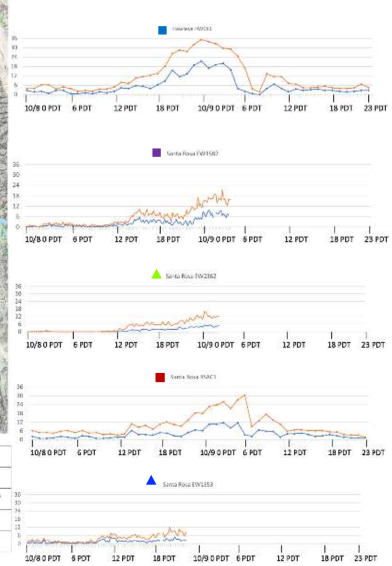


Image courtesy of WeatherFlow
http://blog.weatherflow.com/high-pressure-wind-event-diablo-santa-ana-el-norte-winds/

Local mesonet provided an unclear message about what was happening





Stronger → Weaker

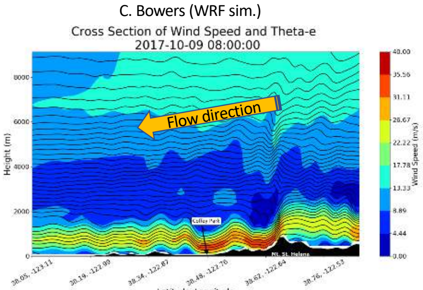
Station	Station	Station
Hawkeye HWCK1	Santa Rosa Sonoma County Airport KSTS	Santa Rosa EW2362
Santa Rosa RSAC1	Atlas Peak ATLC1	Lower Bennett Valley BVYWW
Lake County RAWS1 LKRC1	Lower Lake EW5568	Santa Rosa CW3628
Kenwood KENWW	Santa Rosa DW9840	Santa Rosa EW1553
Santa Rosa EW1582		

Regional simulations with a mesoscale model tell *some* of what happened

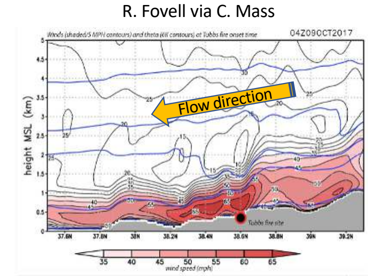
WRF simulations of Oct. 8, 2017

- Operational models produce strong winds over ridges
  - HRRR: 25-28 m/s near Santa Rosa
- Mesoscale model (WRF) research simulations
  - C. Bowers, R. Fovell WRF sims: peak ~ 31 m/s

C. Bowers (WRF sim.)

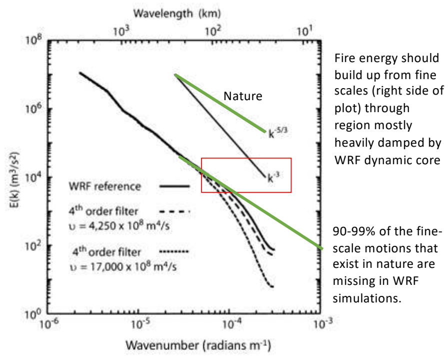


R. Fovell via C. Mass



The predicted winds at the Tubbs site was scary strong, with max winds around 70 mph.

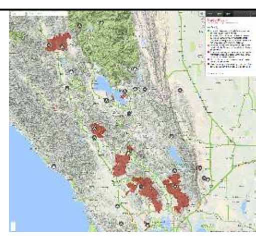
The numerical algorithms in WRF vigorously suppress small scale motions



Skamarock, W.C. Evaluating mesoscale NWP models using kinetic energy spectra. *Mon. Weather Rev.* **2004**, *132*, 3019–3032.

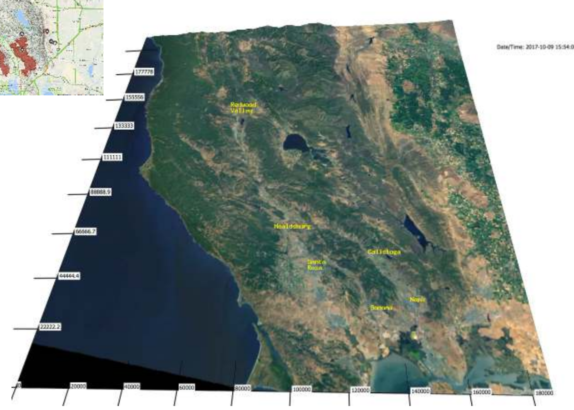
Results:

- Small, sharp gradients (i.e. extrema) are smoothed out
- In WRF-based coupled weather-wildfire “real” simulations, local winds driving the wildfires, fire phenomena, and wildfire shape are unnaturally smoothed out



4D weather simulated using the CAWFE model

Shown: near-surface wind from Oct. 8 11 am – Oct. 9 ~4 PM PDT



Wind speed arrows point downwind & are colored according to this color bar.

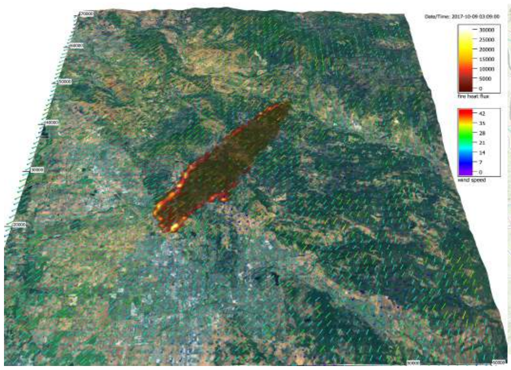
3-domains (10, 3.3, and 1.1 km horizontal grid spacing).

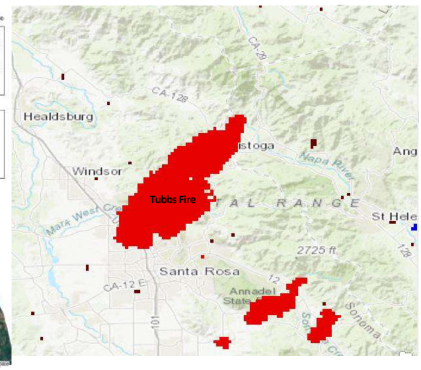
30 m/s : ~ 67 m.p.h
40 m/s : ~ 90 m.p.h.

Imagery produced by VAPOR (www.vapor.ucar.edu), a product of NCAR’s Computational Information Systems Laboratory.

Coen, Schroeder, and Quayle (2018) Atmosphere.

CAWFE simulation of the Tubbs Fire Oct. 8 9 PM – Oct. 9 6:45 AM





Visible and Infrared Imaging Radiometer Suite (VIIRS) active fire detections at 3:09 A.M. Oct 9. 2017

Using IR data to estimate the extent of the flaming front in ember storms is ambiguous.

Coen, Schroeder, and Quayle (2018) Atmosphere.

Simulated wind peaks exceed 40 m s^{-1} (~90 mph) on secondary ridges

Vertical cross section along flow over Tubbs fire
Contours: speed in plane

- Shallow (< 1500 m) high speed flow of stable air
  - Surges from upstream move through
- But, Fr >> 1
  - kinetic forces ⟺ >> buoyancy ↕ forces i.e. too fast for stability effects (like waves).
- Meteorological theory: Expect behavior like neutrally-stratified flow, with acceleration over ridges
  - **Our results**: *Mostly*, but eddies of extremely fast air shed & flow downstream
- Eddies get additional acceleration over secondary ridges, boosting peak winds over 40 m s^{-1} .
  - Ex: Tubbs ignition area

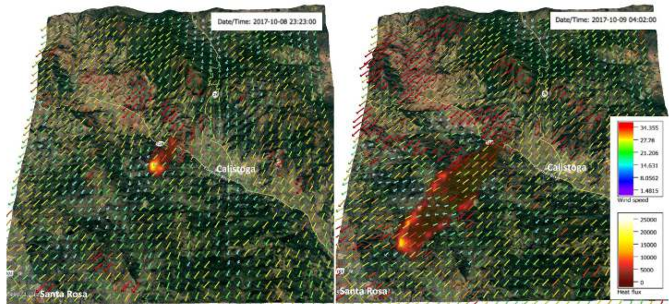
Coen, Schroeder, and Quayle (2018) Atmosphere.

CAWFE Configured as a faster than real-time forecast

Integrated with VIIRS satellite active fire detection data, CAWFE is being applied as a forecast.

A configuration of 4 nested domains, 370 m grid spacing (4th dom.: ~26km x 26 km)

- Runs 4x faster than real time on *a single workstation processor*
- Sufficient resolution and skill as a 1-2 day forecast tool even for large wildfires



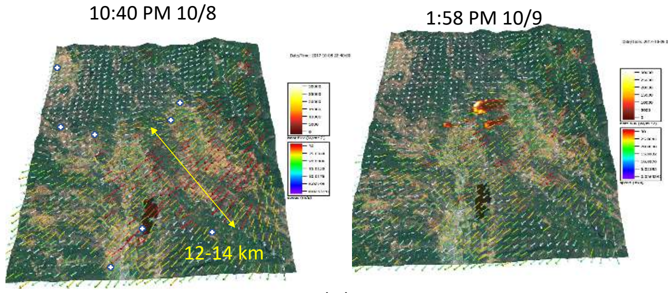
CAWFE forecast of the 2017 Tubbs fire near Calistoga and Santa Rosa, CA. Shown are near-surface winds (colored according to upper color bar) and fire heat flux (colored according to lower color bar) at 11:23 PM PDT Oct 8 and 4:02 AM PDT Oct 9.

Forecasts can be used to predict where a fire will spread, when dangerous behavior like blow-ups and wind shifts will occur, and which locations will be impacted by smoke.

Coen, Schroeder, and Quayle (2018) Atmosphere.

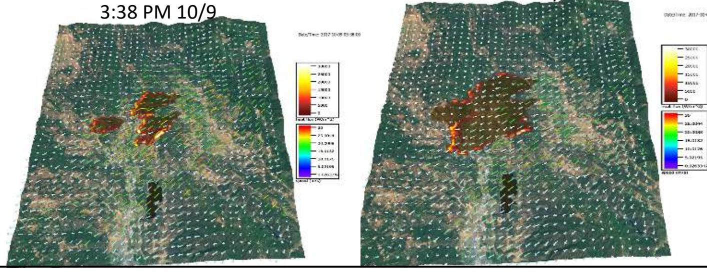
Redwood Valley Fire

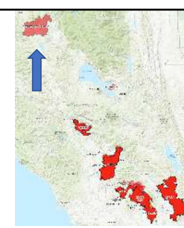
10:40 PM 10/8 — 1:58 PM 10/9



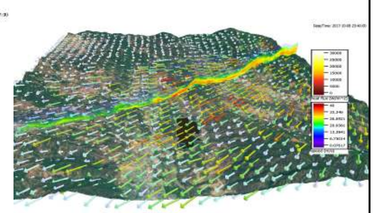
∘ Mesonet stations reporting on 10/8/17

3:38 PM 10/9 — 6:04 AM 10/9

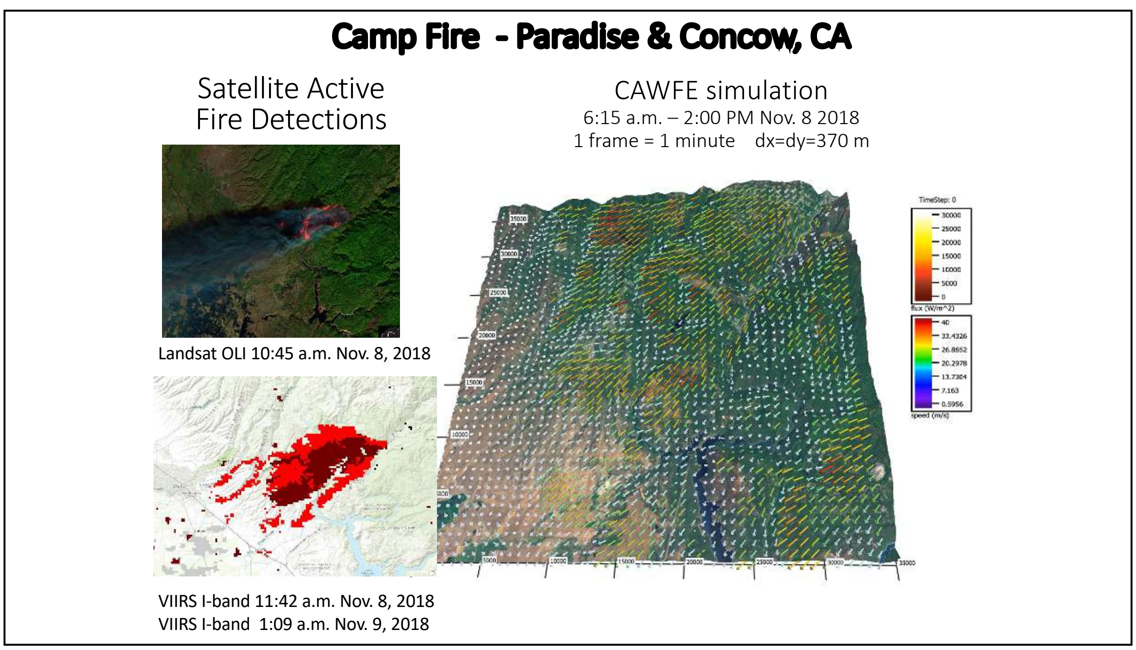




Further north, the pressure gradient drove air over a lower barrier in the Sierras, creating a shallow, narrow river of high speed air that reportedly ignited the Redwood Valley Fire.

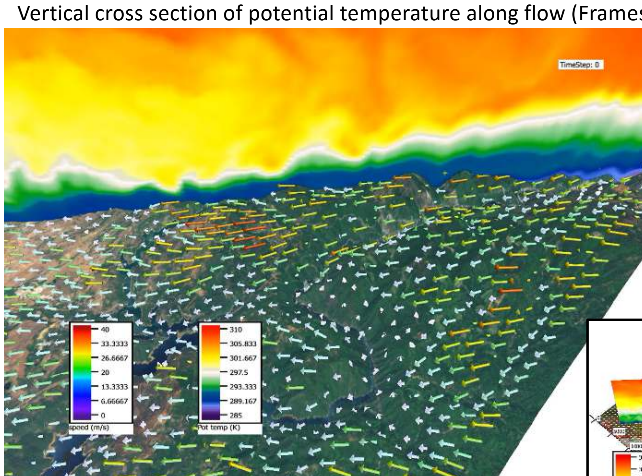



Previous day's warnings....
CA wildfire threats could lead PG&E to cut power to parts of nine counties
11/7/18 SF Chronicle
FIRE DANGER TODAY IS...
HIGH
Area winds at 2 p.m. yesterday
Wind barb: 1 full barb = 10 mph
72 mph gust knocks Mount Diablo as windy conditions around Bay Area increase fire danger
11/8/18 SF Chronicle
Today:
Camp Fire near Paradise, CA. Winds of up to 50 mph, fire grew from 1,000 acres to 5,000 acres by 9:23 am-(SacBee). Now at 18,000 acres. > 25,000 evacuated
The massive plume from the Camp Fire, burning in the Feather River Canyon and near Paradise, wafts over the Sacramento Valley as seen from Chico on Thursday morning. (David Little -- Enterprise-Record)

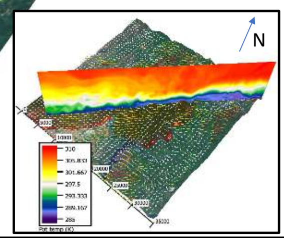

Camp Fire - Paradise & Concow, CA
Satellite Active Fire Detections
Landsat OLI 10:45 a.m. Nov. 8, 2018
VIIRS I-band 11:42 a.m. Nov. 8, 2018
VIIRS I-band 1:09 a.m. Nov. 9, 2018
CAWFE simulation
6:15 a.m. – 2:00 PM Nov. 8 2018
1 frame = 1 minute dx=dy=370 m

Gravity wave dynamics created pulses of strong winds near the surface over the Camp Fire

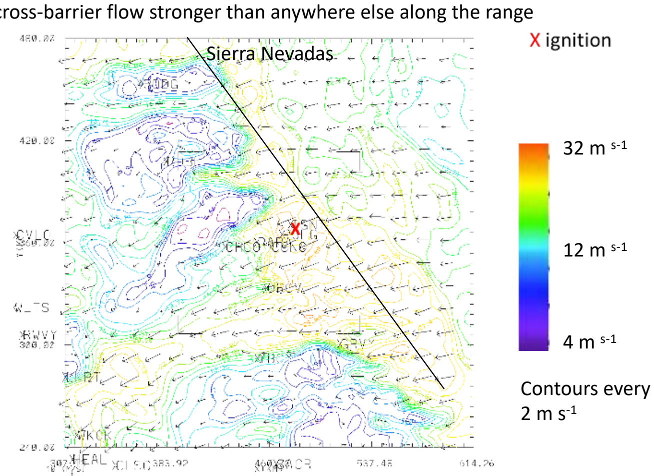
Vertical cross section of potential temperature along flow (Frames: 1 min. intervals)



Vertical cross section location

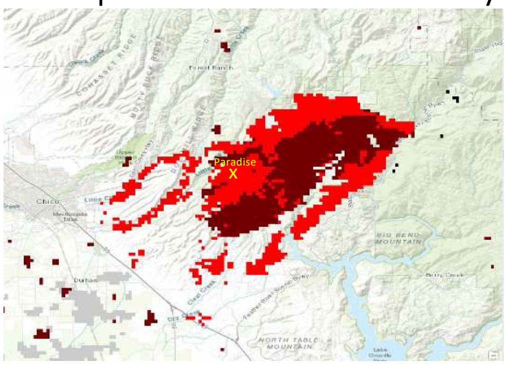


As high pressure inland pushed air over the Sierras toward the coast, a relatively low barrier upwind of Paradise/Oroville created a cross-barrier flow stronger than anywhere else along the range



Plotted: contours of horizontal wind speed at 860 m above ground level

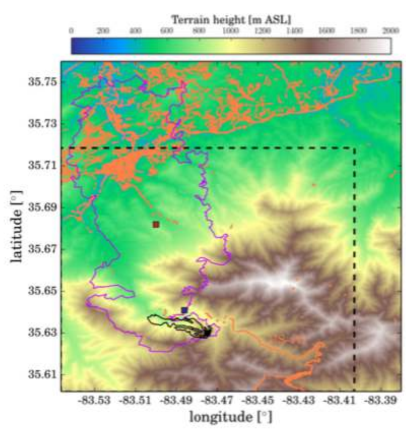
Camp Fire – end of 1st day



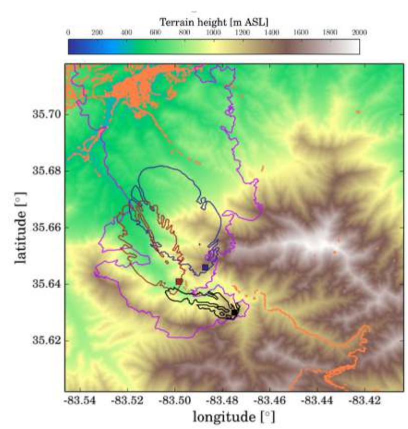
VIIRS I-band 11:42 a.m. Nov. 8, 2018
VIIRS I-band 1:09 a.m. Nov. 9, 2018

Chimney Tops 2 Fire

Simulated with WRF-Fire



Magenta: obs. perimeter
Black: Sim



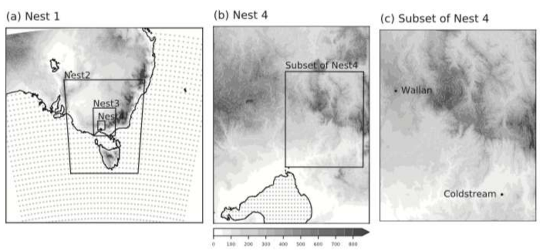
Magenta: obs. perimeter
Black: Sim
Dark blue: Sim with "spotting"

Jimenez et al. 2018 *Atmosphere*

Fire module in a global atmospheric model – ACCESS-Fire

Model for wildfire spread within the UKMet unified model with McArthur (1966) ROS.

Victoria fires February 7, 2009 – Kilgore East fire on Black Saturday
Global model: ∆x ~25 km



Toivanen et al. 2019 *JAMES* *(M. Reeder/T. Lane)*

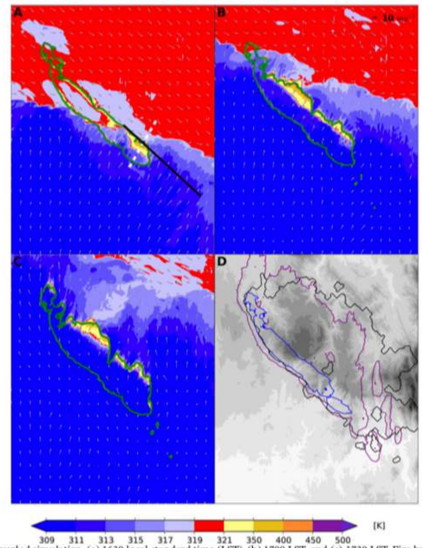
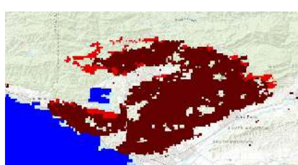


Figure 8. Coupled simulation. (a) 1630 local standard time (LST), (b) 1700 LST, and (c) 1730 LST. Fire boundary (green contour), potential temperature at 5 m above ground level (colored shading), and wind vectors at 13 m above ground level. Note the nonlinear color scale for the potential temperature. (d) Final observed fire boundary (black), final simulated fire boundary taken to be 0730 LST 8 February 2009 (purple), and simulated fire boundary just before the frontal change (blue). Orography contours (gray shading every 100 m).

Complex Events

Some fires have wind-driven and plume-driven components

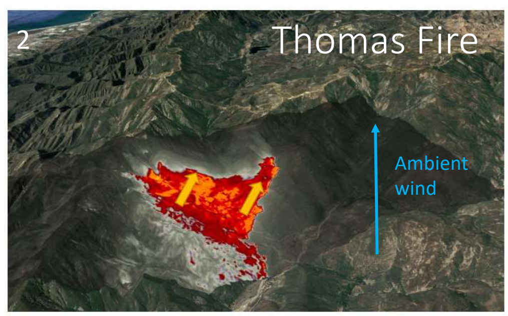


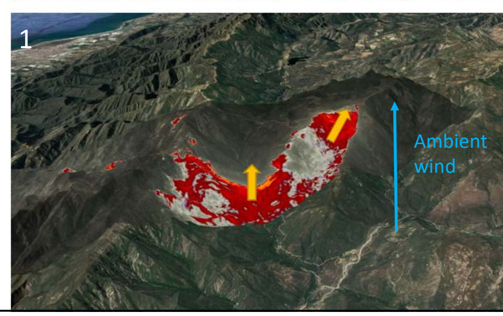
VIIRS detection on 12/10/17

Fire-induced winds are created as fire draws itself up topographic bowl

- A particularly dangerous safety hazard
- Firefighter fatality in drainage 12/15

USFS Airborne infrared data collected on 12/9/17
(P.J. Riggan, USFS)



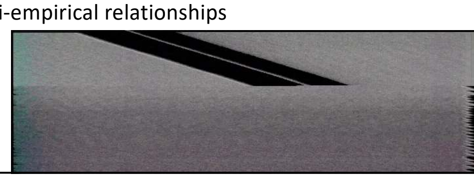


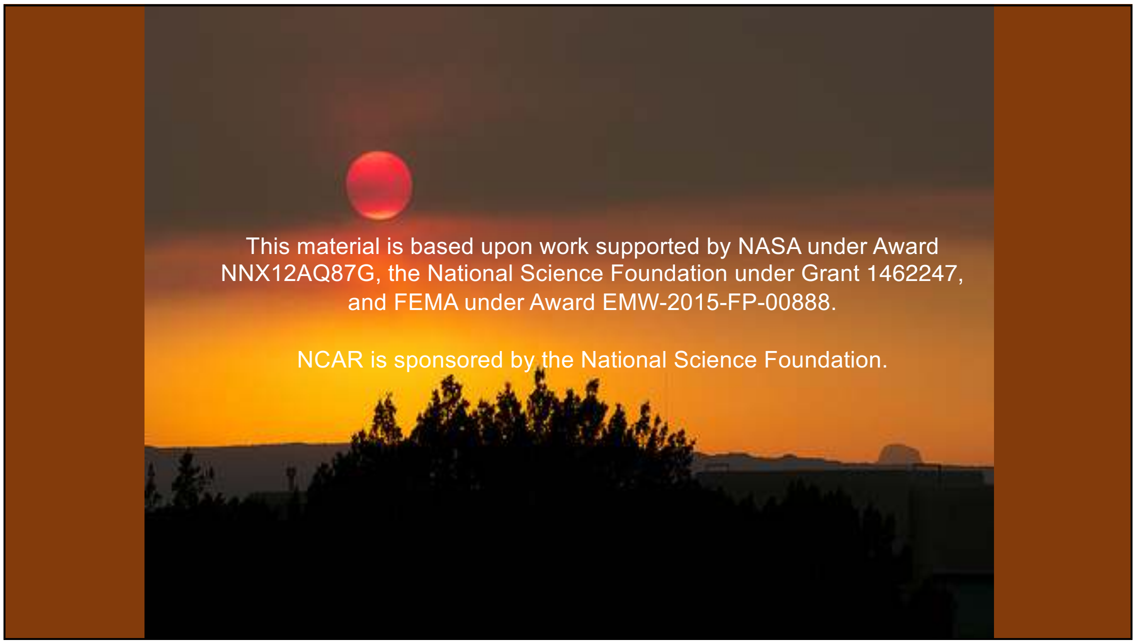
Embers in landscape-scale fires

- In landscape-scale fires, transport is in terrain- and fire-modified winds.
- Affected by turbulence.
  - Another process negatively impacted by model smoothing
- Embers can play many different roles
  - Long-distance spotting of individual embers
  - May/may not be overrun by flaming front before can create convection
  - Given an ember storm, is discussion of propagation of a 'flaming front' meaningful?
- Complicate interpretation of satellite active fire detection data to be used as validation

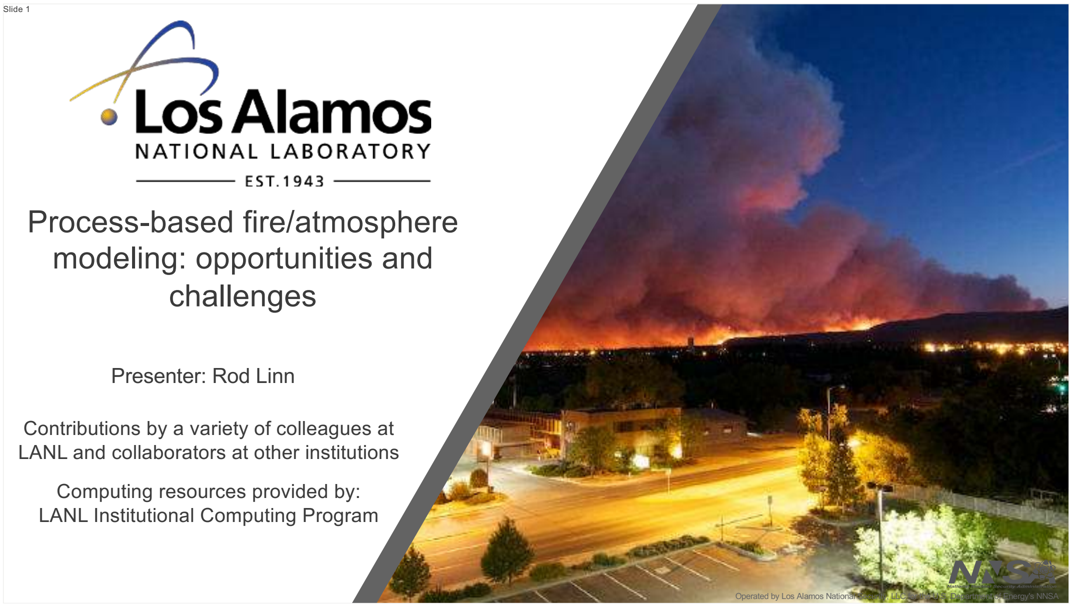
Summary

- Coupled weather – fire models can be useful tools for addressing certain types of questions
  - Ex.: To investigate how the heat fluxes released by a fire, atmospheric dynamics, and thermodynamics shape fire behavior, phenomena, and events. For this, simple fire processes parameterizations, in a coupled framework, often suffice.
  - Distinct from other finer-scale models/studies that focus in more detail on combustion, heat transfer, and mode of propagation
- The integration of numerical weather prediction with fire science has allowed advances …
  - In retrospectively simulating landscape-scale wildland fire events.
    - Success has hinged on meteorological model's design, configuration, and ability to reproduce microscale flows
  - And, with the introduction of remote sensing fire detection data, a methodology to forecast the growth of fires throughout their lifetimes, with performance faster than real time
- Current issues:
  - Crown fires unlikely to be satisfactorily addressed with semi-empirical relationships
  - WUI issues – Embers, Fuel characterized as unburnable




This material is based upon work supported by NASA under Award NNX12AQ87G, the National Science Foundation under Grant 1462247, and FEMA under Award EMW-2015-FP-00888.
NCAR is sponsored by the National Science Foundation.

Appendix E.3 Rod Linn (LANL)



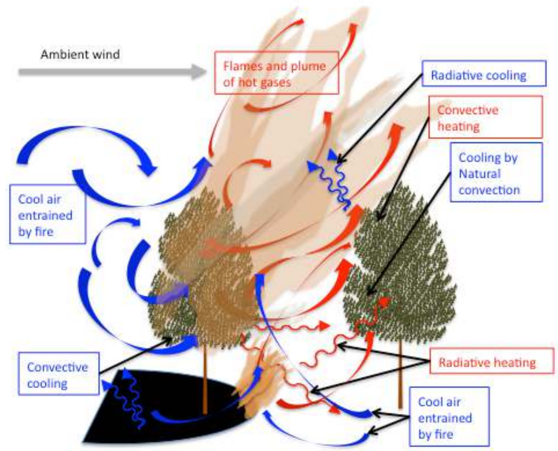
The role of physical process-based modeling in wildfire behavior research

- Fire experiments and field observations*:
  - Complete physics
  - Partially disclosed
- Process-based fire behavior modeling*:
  - Partial physics
  - Completely disclosed
- Models can help **test our understanding**.
- Models can assist in the **development of hypotheses**, which should be tested with observations.
- Models can allow **scenario and sensitivity explorations** when observations are difficult.
- It is important to **keep in mind the assumptions/approximations** of model formulations (only partial physics).

*Notion borrowed from Sheldon Tieszen, Sandia National Laboratory (original or obtained from some unkown source)

Physics-based or "process-based" modeling

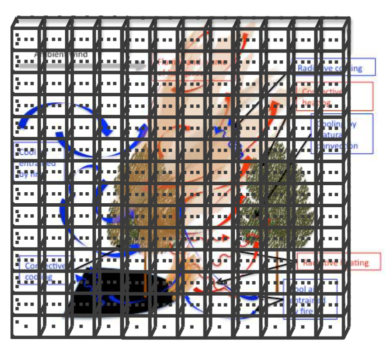
Attempt to represent critical processes that determine wildfire behavior



Can not resolve everything and still capture landscape scales

Attempt to represent critical processes that determine wildfire behavior

- **Explicitly resolved**
  - Macro-scale advection of quantities
  - Effects of topography
  - Influences of macro-scale fuel structure
  - Large-scale buoyancy-induced flows
- **"Sub-grid" or "Sub-data" processes:**
  - Fine-scale temperature distribution within a grid cell
  - Fine-scale mixing, chemistry, and combustion processes
  - Fine-scale turbulence
  - Momentum and heat exchange between solids and gases.



Can not resolve everything and still capture landscape scales

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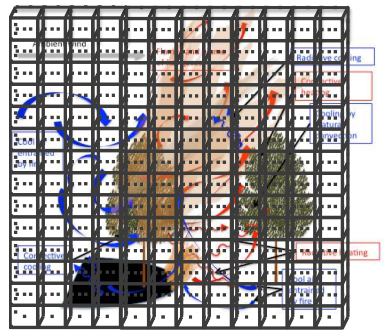

Significant challenge

Fuels description

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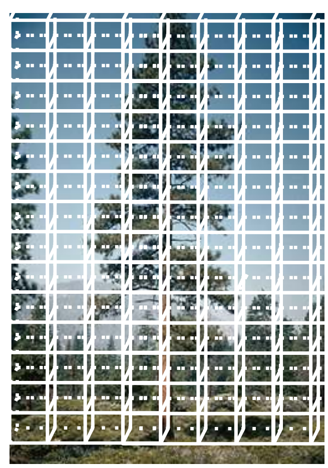
Examples of processes influenced by vegetation

- Aerodynamic drag
- Convective and radiative heat transfer
- Moisture exchange
- Reaction rate

Three-dimensional volumetric representation of vegetation

- Local vegetation properties
- Inputs currently used
  - Size and shape of foliage
    - Characteristic size scale or surface area per unit volume
  - Bulk density
  - Moisture content
    - mass of water/mass of dry fuel
  - Height of fuel



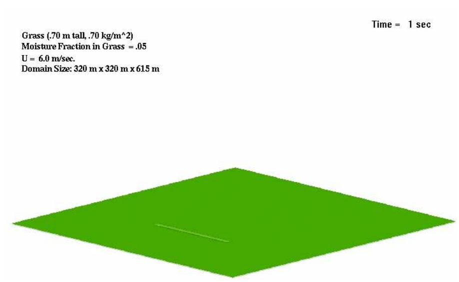
Considerations for choosing process-based modeling tools

- Required size of domain
- Computational cost
- Model formulation/assumptions
- Do the fidelity of the inputs match expectation of result accuracy/precision?
  - Winds
  - 3-D fuels
- Scales of phenomenology of interest
- Scales of fire behavior

Especially big challenges for simulations in WUI scenarios

Opportunity: Explore fundamental aspects of wildland fire behavior

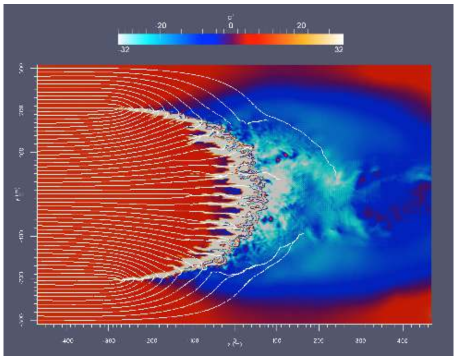
Wildfire behavior depends on a wider set of variables many of which are influenced by the fire itself.



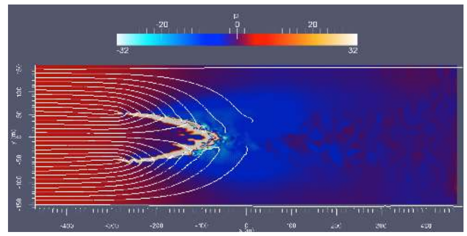
Linn, R. R., Cunningham, P., 2005: "Numerical simulations of grassfires using coupled atmosphere-fire model: Basic fire behavior and dependence of wind speed." *J. Geophys. Res.*, **110**, D131007, doi:10,1029/2004JD005/597.

Fire-scale 3D effects (shape/length effects)

2D streamlines and pressure perturbations



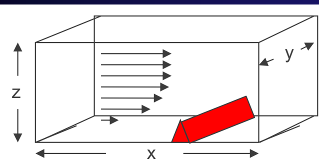
Ignited from a 400 m long fireline



Ignited from a 100 m long fireline

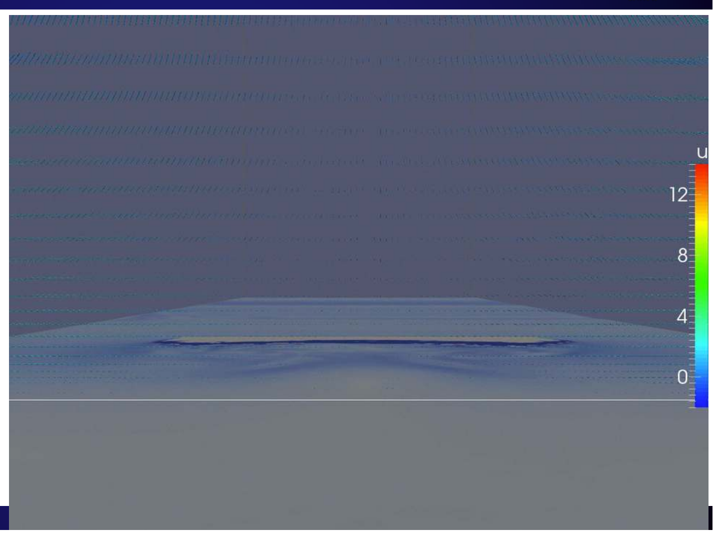
Canfield J.M., Linn R.R., Sauer J.A., Finney M., J. Forthofer (2014), "A numerical investigation of the interplay between fireline length, geometry, and rate of spread", Agricultural and Forest Meteorology, **189–190**(1): 48-59.

In the past, wildfires have been modeled as a wall of flame.



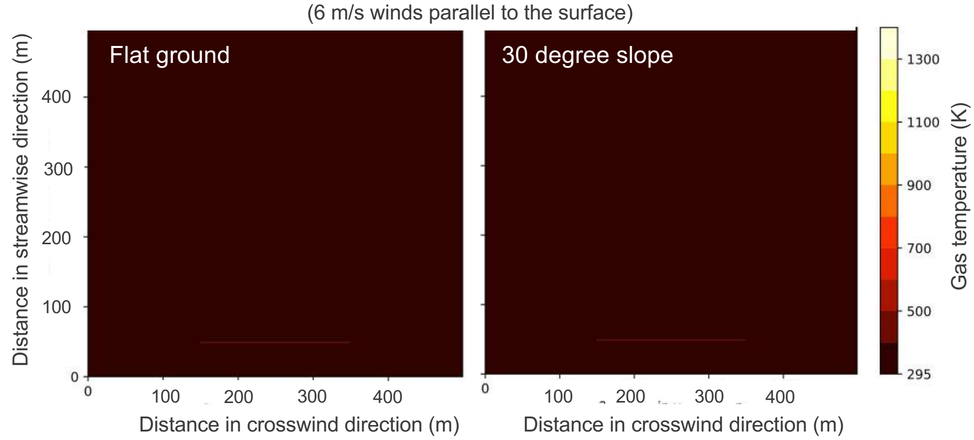
"Wall of flame" concept simplifies fast-running-model development by turning it into a 1-D or 2D problem.

Unfortunately, wildfires often do not behave like a wall of flame.



Opportunity: Gain a better understanding of the influences of slope

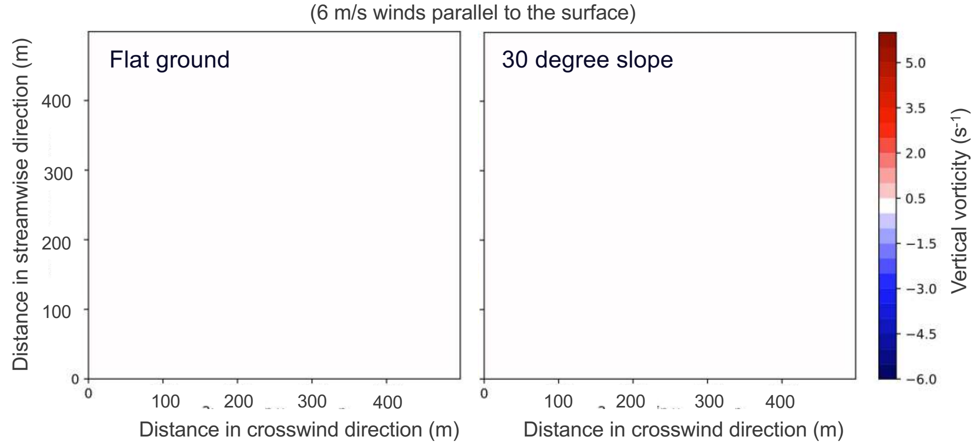
Gas temperature near the surface in couple fire/atmosphere simulations
(6 m/s winds parallel to the surface)



Slide 11

Slope changes on interaction between fire and winds

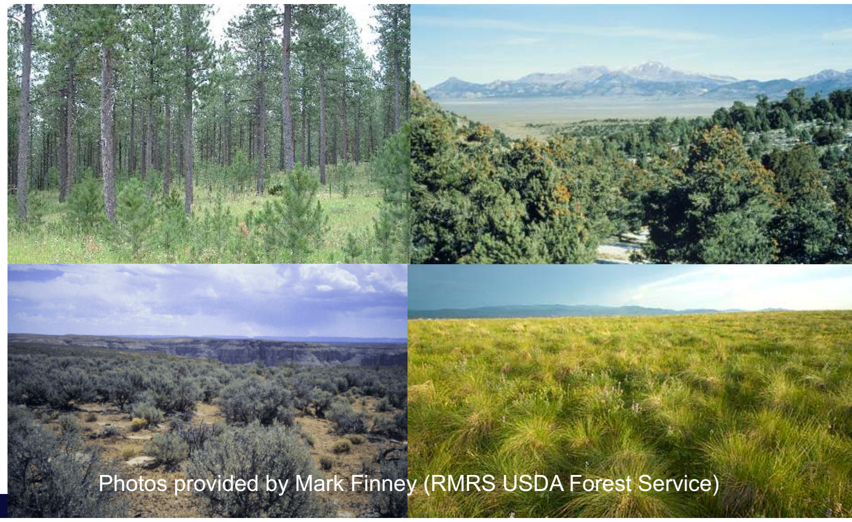
Vertical vorticity near the surface near the surface in couple fire/atmosphere simulations
(6 m/s winds parallel to the surface)



Slide 12

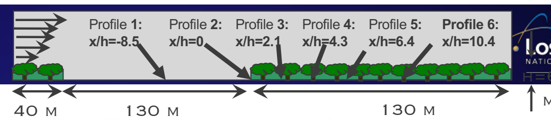
Opportunity:

Explore the influences vegetation heterogeneities

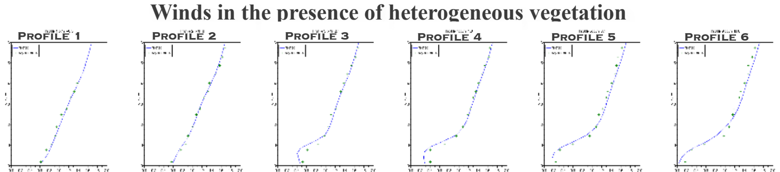


Example:

Influences of fuel breaks on winds

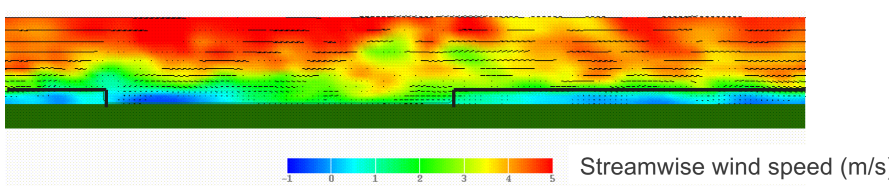


Winds in the presence of heterogeneous vegetation



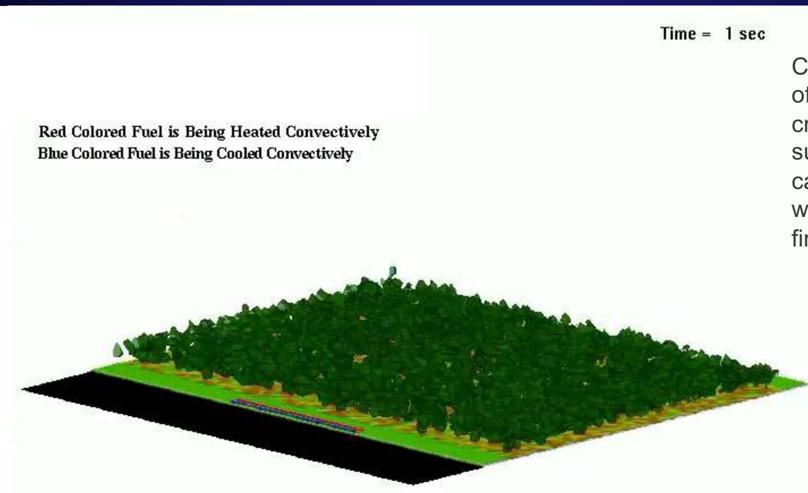
Dynamic wind interaction with heterogeneous forests influences:

- Heat transfer throughout the forest canopy
- Moisture distributions within canopy and at the surface



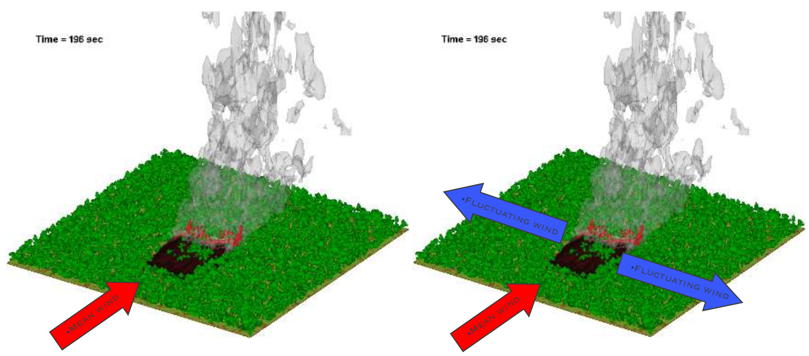
Pimont F., Dupuy J-L., Linn R.R. and Dupont S. (2009). "Validation of FIRETEC wind-flows over a canopy and a fuel-break." International Journal of Wildland Fire **18**(7): 775-790.

Fire/atmosphere/vegetation feedbacks that influence forest resilience to fire



Convective cooling of canopy foliage is critical for the survival of forest canopies, even with low intensity fires

Can lateral spread be predicted without accounting for crosswind fluctuations?

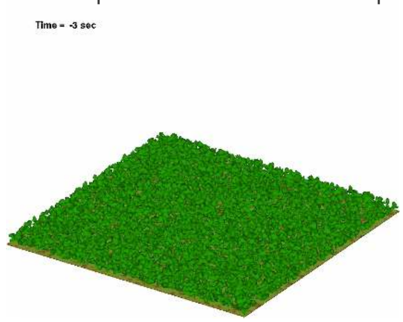


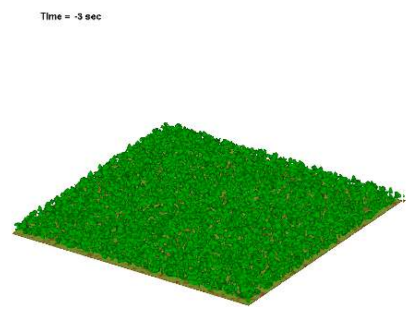
No resolved incoming ambient crosswind fluctuations

Add oscillating crosswind fluctuations, but maintain the same mean wind

Explore impacts of wind fluctuations

Simple sinusoidal fluctuations perpendicular to mean wind





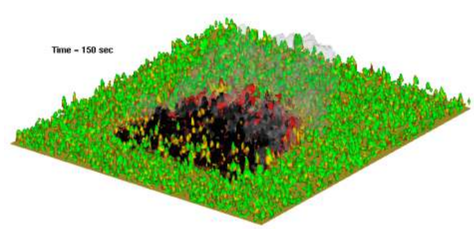
- Crosswind fluctuation maximum amplitude = .5 mean wind
- period =15 sec
- Winds ranging +/- 26 degrees from ambient

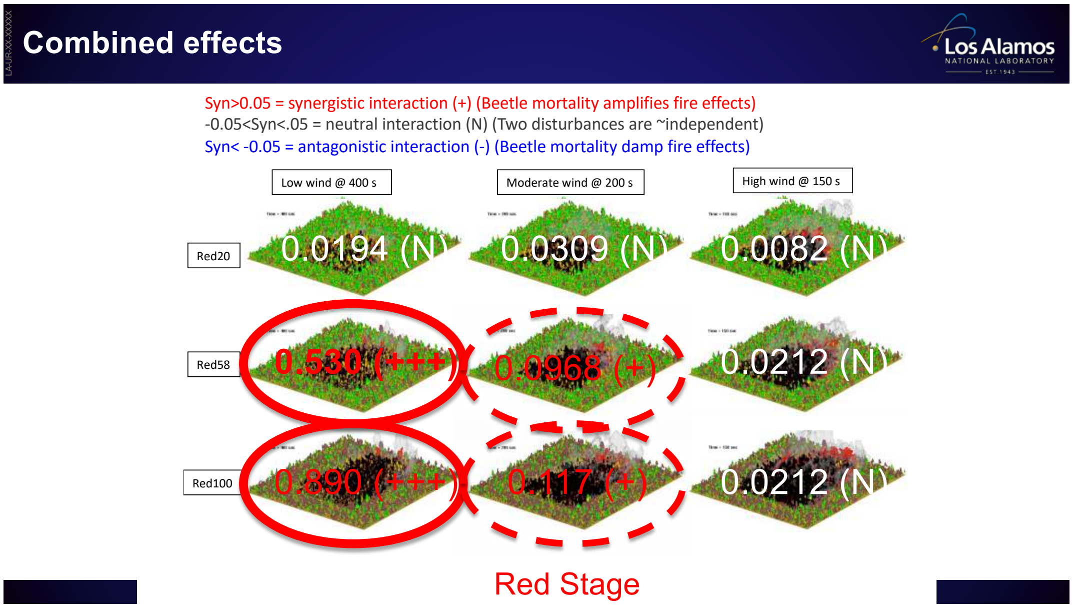
- Crosswind fluctuation maximum amplitude = mean wind
- period = 15 sec
- Winds ranging +/- 45 degrees from ambient

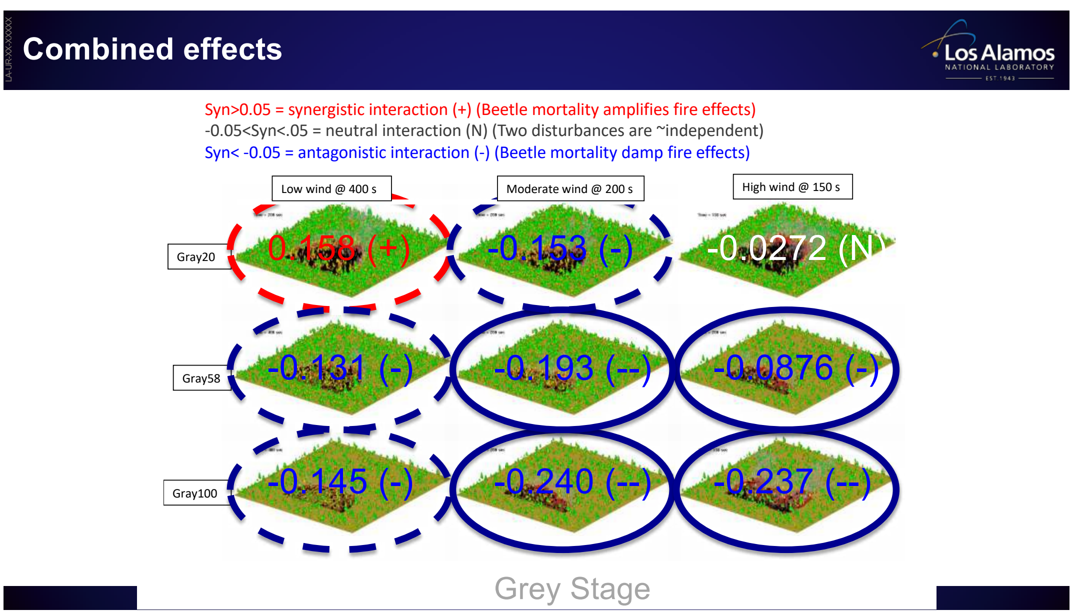
Understanding interaction between multiple disturbances

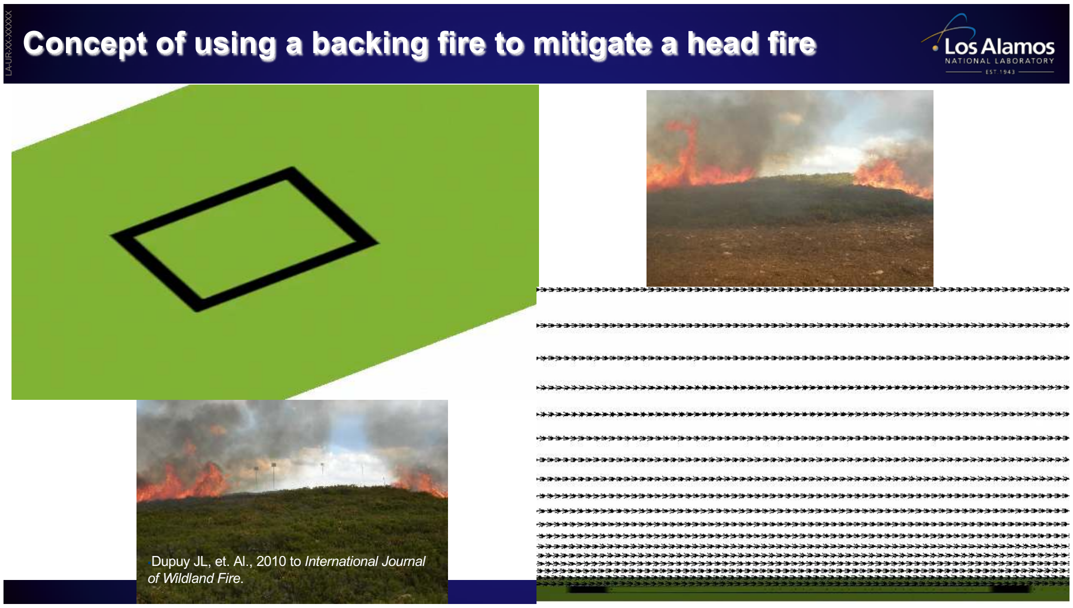
- **Ponderosa pine forest after bark-beetle mortality**
  - **3 levels of insect mortality** 20%, 58%, and 100%
  - **Red and gray** stages of mortality
  - **3 wind speeds** 10, 20 and 40 m s^{-1} at 100 m above surface

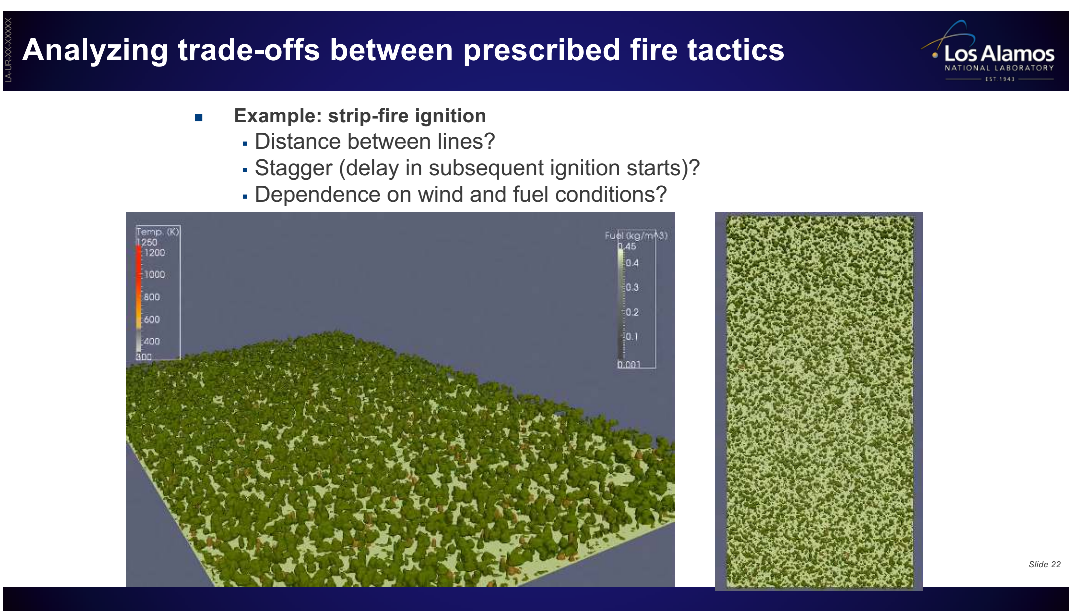

Large expanses of forest have been impacted by recent insect outbreaks




Combined effects
Syn>0.05 = synergistic interaction (+) (Beetle mortality amplifies fire effects)
-0.05<Syn<.05 = neutral interaction (N) (Two disturbances are ~independent)
Syn< -0.05 = antagonistic interaction (-) (Beetle mortality damp fire effects)
Low wind @ 400 s
Moderate wind @ 200 s
High wind @ 150 s
Red20
0.0194 (N)
0.0309 (N)
0.0082 (N)
Red58
0.530 (+++)
0.0968 (+)
0.0212 (N)
Red100
0.890 (+++)
0.117 (+)
0.0212 (N)
Red Stage

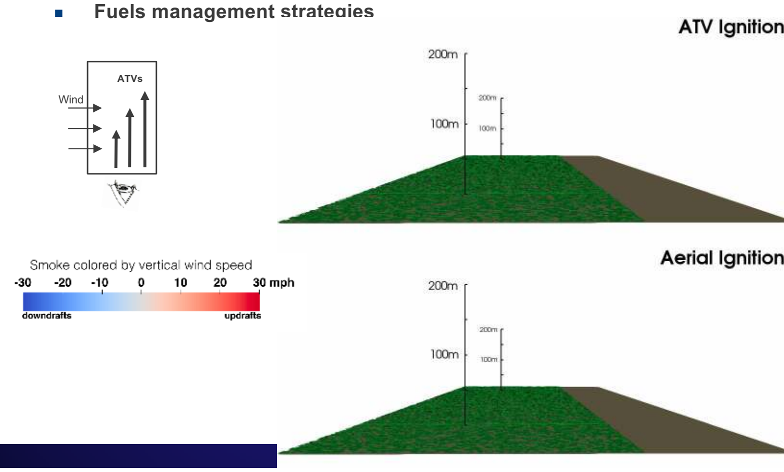

Combined effects
Syn>0.05 = synergistic interaction (+) (Beetle mortality amplifies fire effects)
-0.05<Syn<.05 = neutral interaction (N) (Two disturbances are ~independent)
Syn< -0.05 = antagonistic interaction (-) (Beetle mortality damp fire effects)
Low wind @ 400 s
Moderate wind @ 200 s
High wind @ 150 s
Gray20
0.158 (+)
-0.153 (-)
-0.0272 (N)
Gray58
-0.131 (-)
-0.193 (--)
-0.0876 (-)
Gray100
-0.145 (-)
-0.240 (--)
-0.237 (--)
Grey Stage


Concept of using a backing fire to mitigate a head fire
Los Alamos
NATIONAL LABORATORY
EST. 1943
Dupuy JL, et. Al., 2010 to International Journal of Wildland Fire.


Analyzing trade-offs between prescribed fire tactics
Los Alamos
NATIONAL LABORATORY
EST. 1943
Example: strip-fire ignition
Distance between lines?
Stagger (delay in subsequent ignition starts)?
Dependence on wind and fuel conditions?
Temp. (K)
1250
1200
1000
800
600
400
300
Fuel (kg/m^3)
0.45
0.4
0.3
0.2
0.1
0.001
Slide 22

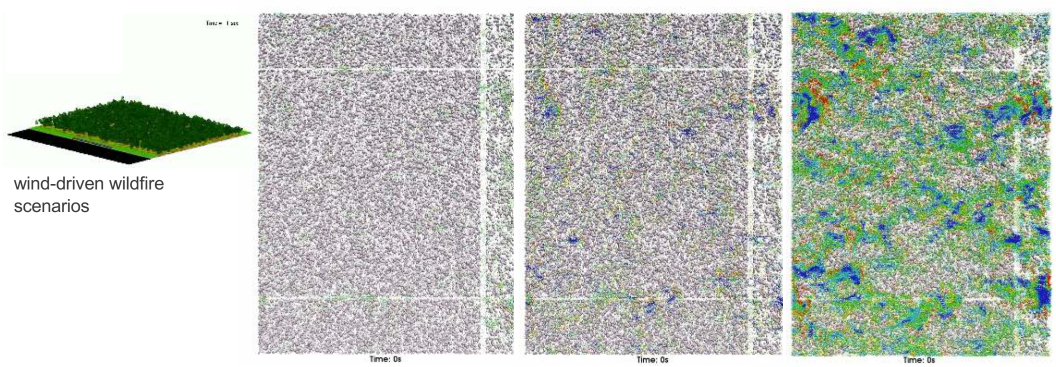
Studying opportunities to engineer plume behavior

- Prescribed fire
- Fuels management strategies



Difference in wind paradigms: prescribed fire vs. wildfires

Vertical winds in vicinity of low-intensity prescribed fire (aerial ignitions) (5.6 m/s ambient. Wind above canopy)



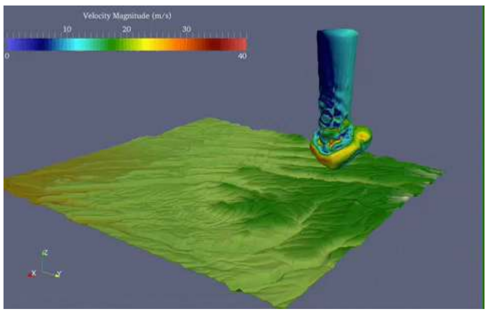
Height=2.5 m
Blue=2 m/s downward
Green=Horizontal winds
Red=2 m/s upward

Height=10 m
Blue=2 m/s downward
Green=Horizontal winds
Red=2 m/s upward

Height=30 m
Blue=4 m/s downward
Green=Horizontal winds
Red=4 m/s upward

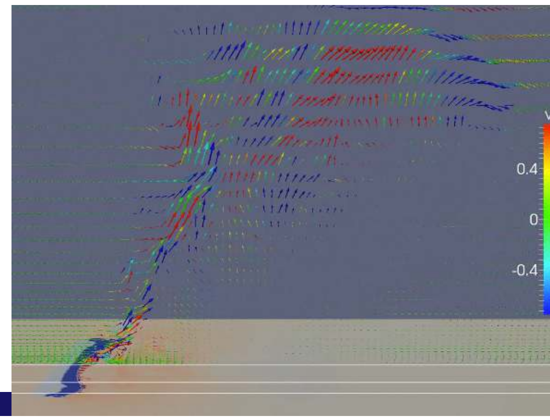
LA-UR-XX-XXXXX

Study low-frequency but high-consequence events



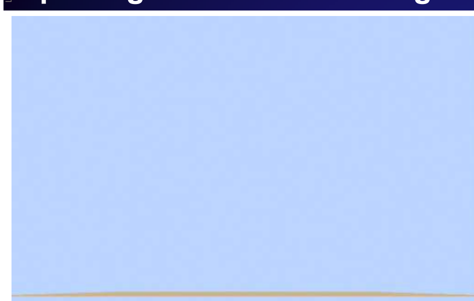
Downwash events cause density current flow patterns

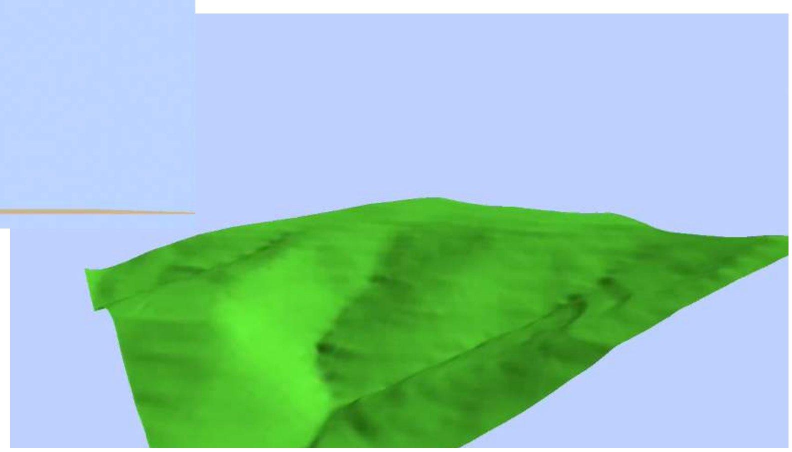
- Moving faster than ambient winds
- Containing “back-spin” vorticity
- Amplifies multiple aspects of fire



LA-UR-XX-XXXXX

Understanding how environmental factors influence spotting or firebrand lofting and transport

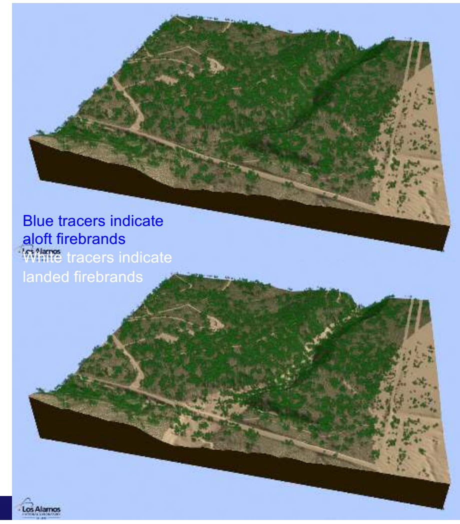




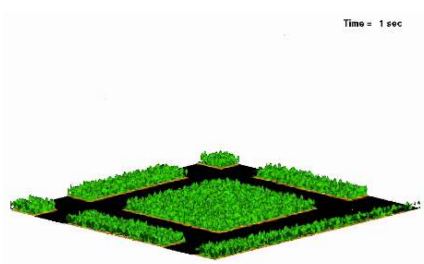
Searching for opportunities to engineer wildfire behavior

Simulations suggest potential impact of strategic fuels treatment (or gully-washing rain events) for managing fire risk at this facility from continuous fire spread.

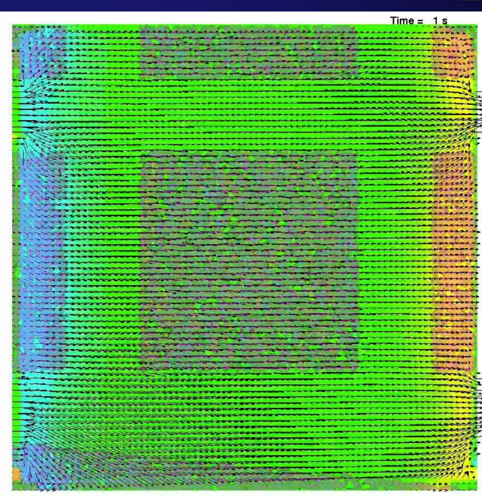
However, these simulations also remind us of the importance of considering longer range spotting for facility protection.



Enhancing the value of fire experiments through simulations



International Crown Fire Modeling Experiment Plot 1



Linn et. al. (2005) AMS Forest and Fire Meteorology Symposium

Challenge:

Trying to pair modeling with field experiments

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2012 RxCADRE fires

- On Eglin AFB
- "Highly" instrumented
- Low intensity fires

Plot S5 Plot size: 100 m x 200m

- Surface fuels only (not trees)
- Homogeneous from **macroscale perspective**

Challenges:

Assessing and ingesting heterogeneous fuels

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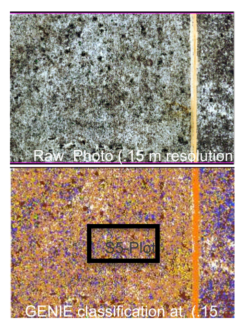
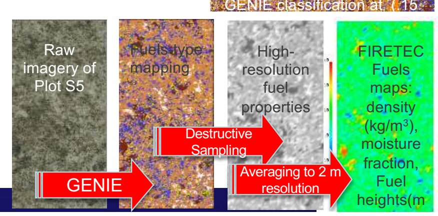
- 2010 high-resolution aerial photography (15 cm resolution)
- GENIE image analysis trained through iterative process and site verification to classify each pixel into one of these 7 classes:

  - Short grass
  - Tall grass
  - Palmetto
  - Road
  - Bare ground
  - Little blue stem
  - Woody goldenrod

- Refined training of GENIE using numerous attributes from individual verification sites





Challenges:

Using measured velocities to stipulate winds in simulations

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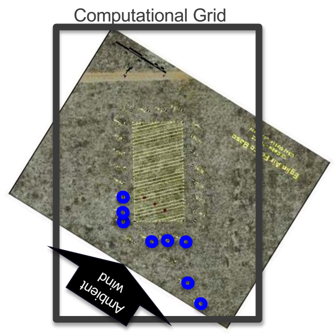
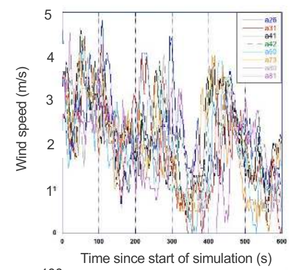
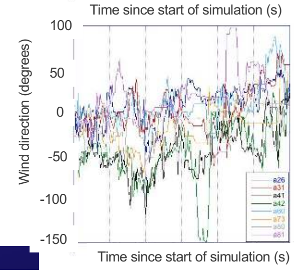


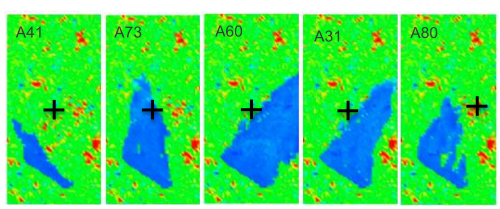
8 upwind anemometers (2.5 m tall)
- Wide range of variability
- Large signal to noise ratio

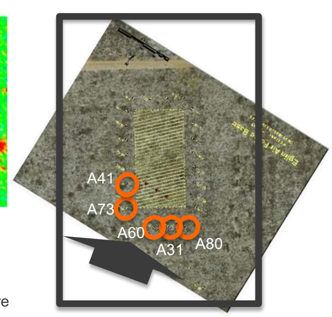




Using single towers to specify winds

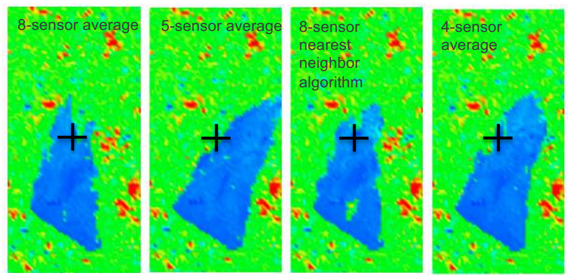
Los Alamos NATIONAL LABORATORY EST. 1943



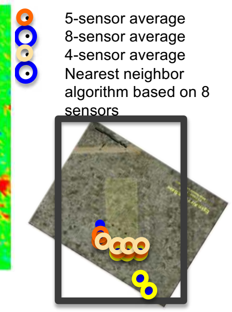


FIRETEC simulations at 320 s (approximate time when RxCADRE fire burned past tower at the center of the plot)

Using multiple towers to specify winds



FIRETEC simulations at 320 s (approximate time when RxCADRE fire burned past tower at the center of the plot).



Using process-based models to further understanding of wildland Fire

Important to remember that they are still just models

Continually look for validation opportunities (field or laboratory)

- Data needs are related to environmental/burning conditions (marginal burning conditions may need more detailed data)
- Predictability of fire behavior depends on the relative magnitude of the ambient spread drivers compared to the fluctuations

Can be combined with observations

- Gain perspective on relevance of collected data (how representative is the data in the context of heterogeneities)
- Interpretation of data context
- Design of experiments

Process-based models present opportunities

- Test our understanding.
- Development of hypotheses
- Develop fast-running simulation tools

Imagine taking point measurements somewhere in this plane