# Coupled Weather-Fire Modeling Across Scales for Biomass Emissions

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# OUTLINE

- Wildland fire - weather basics
- Wildland fire weather modeling at fire behavior scales
- Landscape-scale case studies
- Application to biomass emissions studies
- Lingering issues

# Wildland Fire - Weather Basics

# 3 Environmental Factors that affect Wildland Fire Behavior

**Fuel**

Moisture, mass/area, size, hardwood vs. conifer, spatial continuity, vertical arrangement

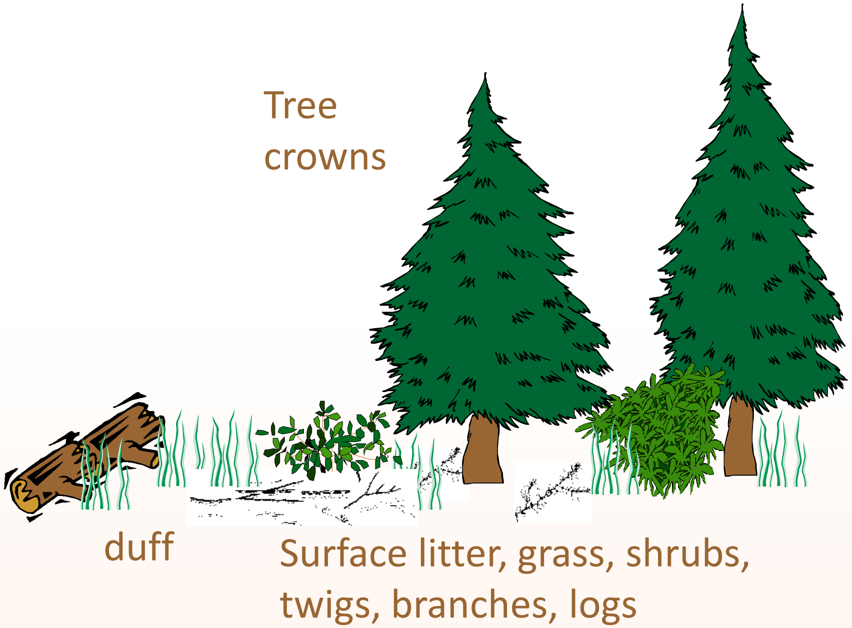
**Weather**

wind, temperature, relative humidity, precipitation

***Weather CHANGES***: fronts, downslope winds, storm downdrafts, sea/land breezes, diurnal slope winds

**Topography**

Slope, aspect towards sun, features like narrow canyons, barriers (creeks, roads, rockslides, unburnable fuel)




*These are not independent*

# Weather

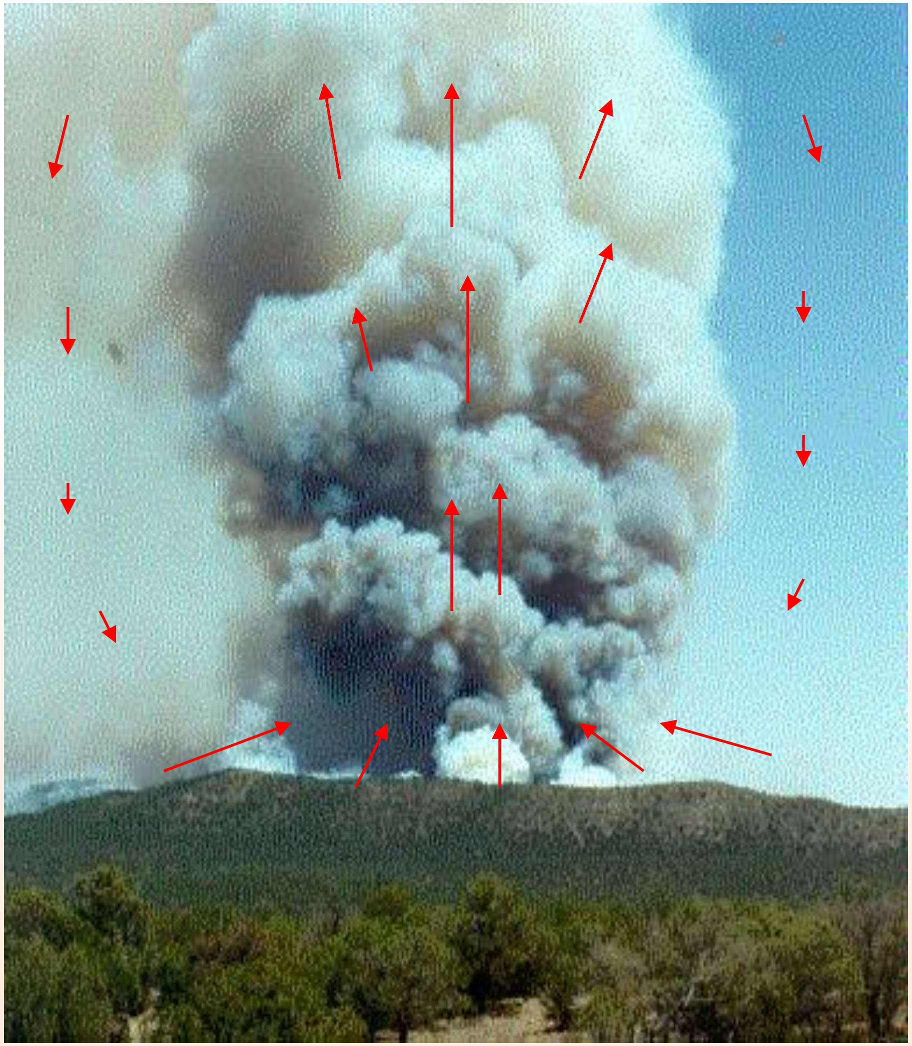
***Weather is one of the most significant factors influencing wildland fire and (compared to terrain and fuel characteristics) the most rapidly changing.***

Weather conditions over wide time and space scales influence:

- where a fire occurs (lightning)
- ignition efficiency
- how fast/where it spreads
- combustion rates
- whether or not the fire produces extreme behavior

# Flow in the vicinity of a fire

- **Updraft**
- **Flow into the base**
- **Compensating downdrafts**



Notes:

- **Air is not 'nothing'.**
- **It has weight & exerts a force.**
- **There are rules about how it can behave.**

# Fire creates its own weather & can change winds over several miles

- Wildland fires don't just respond to weather, they *interact* with the atmosphere surrounding them:
  - The fire releases heat, water vapor into the atmosphere.
  - This alters winds, pressure, humidity, etc. in the fire, in the fire plume, & in the fire environment
  - This in turn feeds back on the fire behavior.

- **This is a basic component of ALL fire behavior**, not just in "plume" vs. "wind" driven, or high vs. low intensity, crown vs. grass fires.

Photo courtesy of Jeff Zimmerman

# How does fire interact with its environment?

Fire whirls


Photo courtesy of Canadian Forest Service

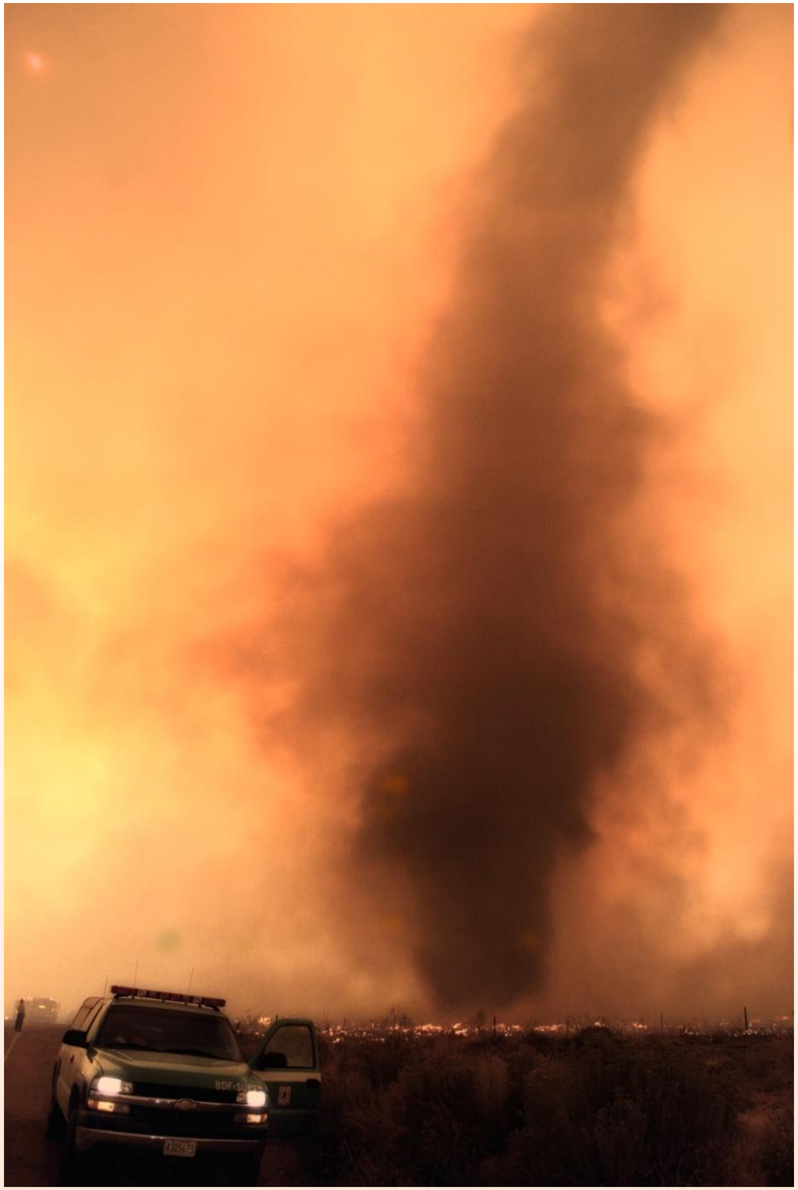


Photo courtesy of Josh Harville

Photo courtesy of Josh Harville

# How does fire interact with its environment?

Convective fingers

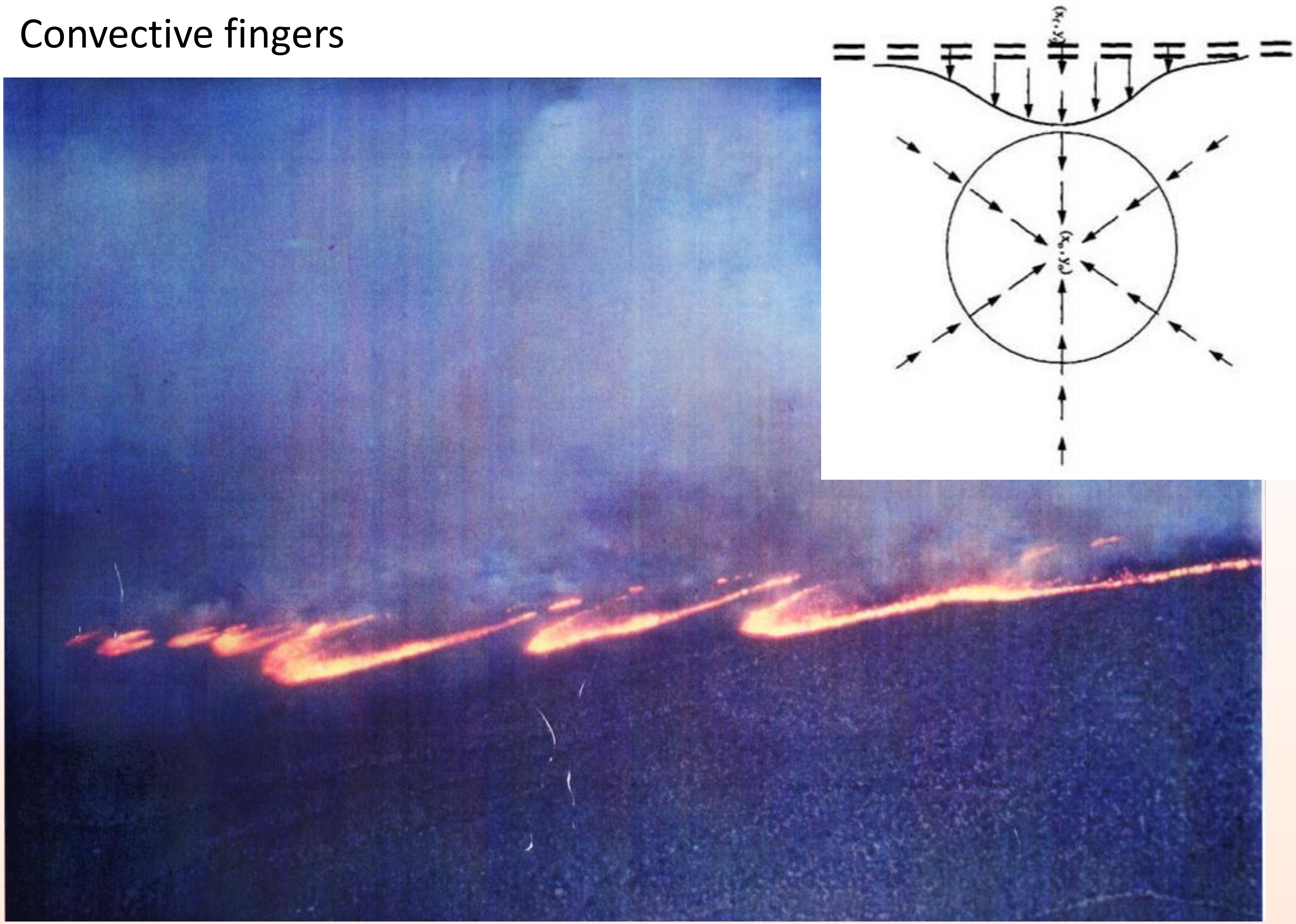


Photo courtesy Charles George, USDA Forest Service

# How does fire interact with its environment?

Turbulent bursts

Photograph courtesy of Jeff Zimmerman

# Wildland Fire Modeling at Fire Behavior Scales

# Wildland Fire Modeling

## A Hierarchy of Models

Increasing complexity

- Experience, Intuition
- Point-based Empirical, semi-empirical equations (i.e. Rothermel 1972)
- 2-D in horizontal, non time dependent (FARSITE)
- 3-D, time dependent, weather model:semi-empirical fire, 10 m – 1 km grids), NCAR/USFS CAWFE, WRF-Fire
- 3-D, time dependent, air flow model:parameterized combustion, 1 m grids - Los Alamos FIRETEC, NIST FDS
- Full combustion treatment (1 cm grids) (does not exist)

*- The ‘best’ one: depends on the constraints of what you are trying to do.*

# Many tools are based on semi-empirical formulas relating rate of spread of the leading edge of the fire line to fuel conditions, slope, and wind.

## Spread Rate of a Flaming Front

(Semi-empirical) Rothermel eqns (1972)

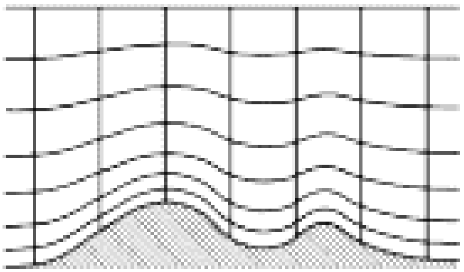
$$R = \underbrace{\frac{I_R \xi}{\rho_b \varepsilon Q_{ig}}}_{\substack{\text{Zero-wind}\\ \text{spread rate on}\\ \text{flat ground}}} (1 + \underset{\substack{\text{wind}\\ \text{factor}}}{\phi_w} + \underset{\substack{\text{slope}\\ \text{factor}}}{\phi_s})$$

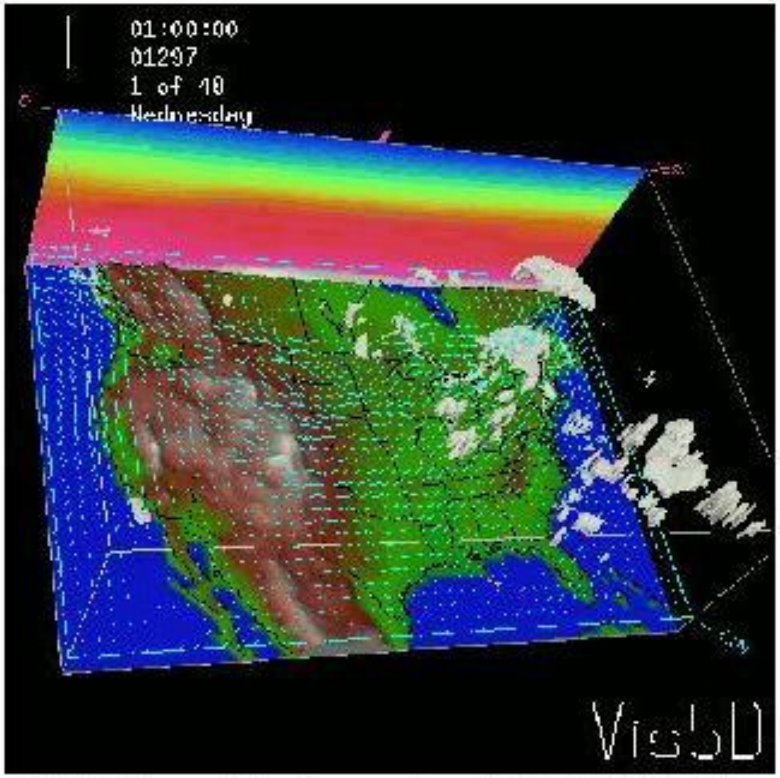
$$\frac{\text{Heat energy of fuel}}{\text{Heat required to prepare fuel \& ignite}}$$

$R_0$ = f(fuel characteristics) (i.e. the type, amount, surface area/volume ratio, heat content, particle density, moisture content, depth, mineral content, moisture content of extinction)

# An Atmospheric ("Weather") Model

Numerical weather prediction models solve predictive equations of fluid motion to forecast air velocity, temperature, water vapor, cloud water, rain, and ice on a grid in a 3-dimensional box.






- **While modeling flow over U.S., can telescope to model flow over single mountain valley with high resolution**
- **Models atmospheric structures like fronts, windstorms, formation of clouds, rain, and hail in "pyrocumulus" clouds over fires**

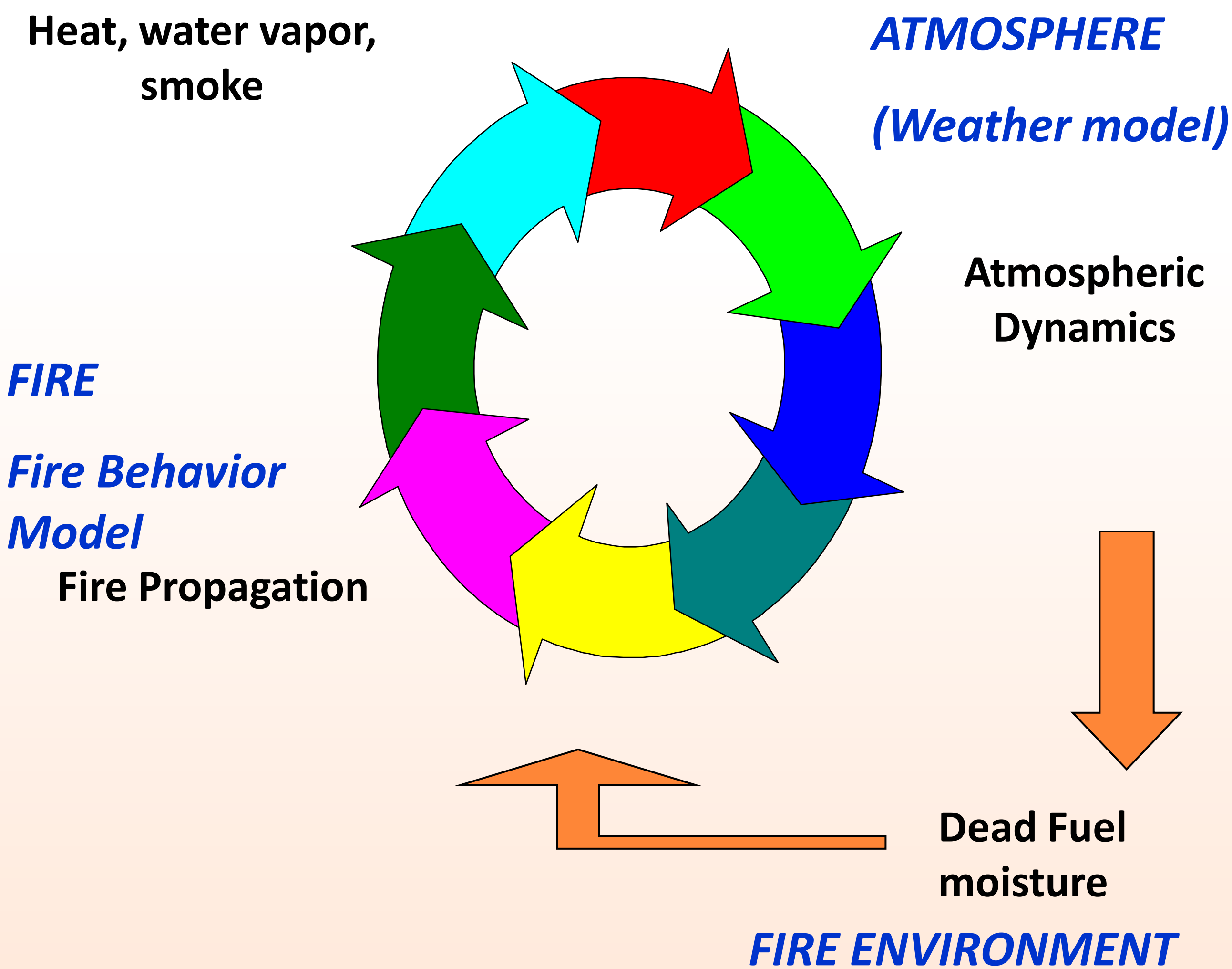
# Wildland Fire Modeling

- Concept of "fire line" – interface between burned and fuel that has not yet ignited

- Important output quantities: Rate of spread (ROS) of the leading edge of the flaming front, intensity, flame length
- In *dynamic* models (where forces are calculated), spatial and temporal variability of consumption is also very important

# Coupled Weather – Wildland Fire models

## 2-way coupling



# Fire Model

**Contains components representing:**

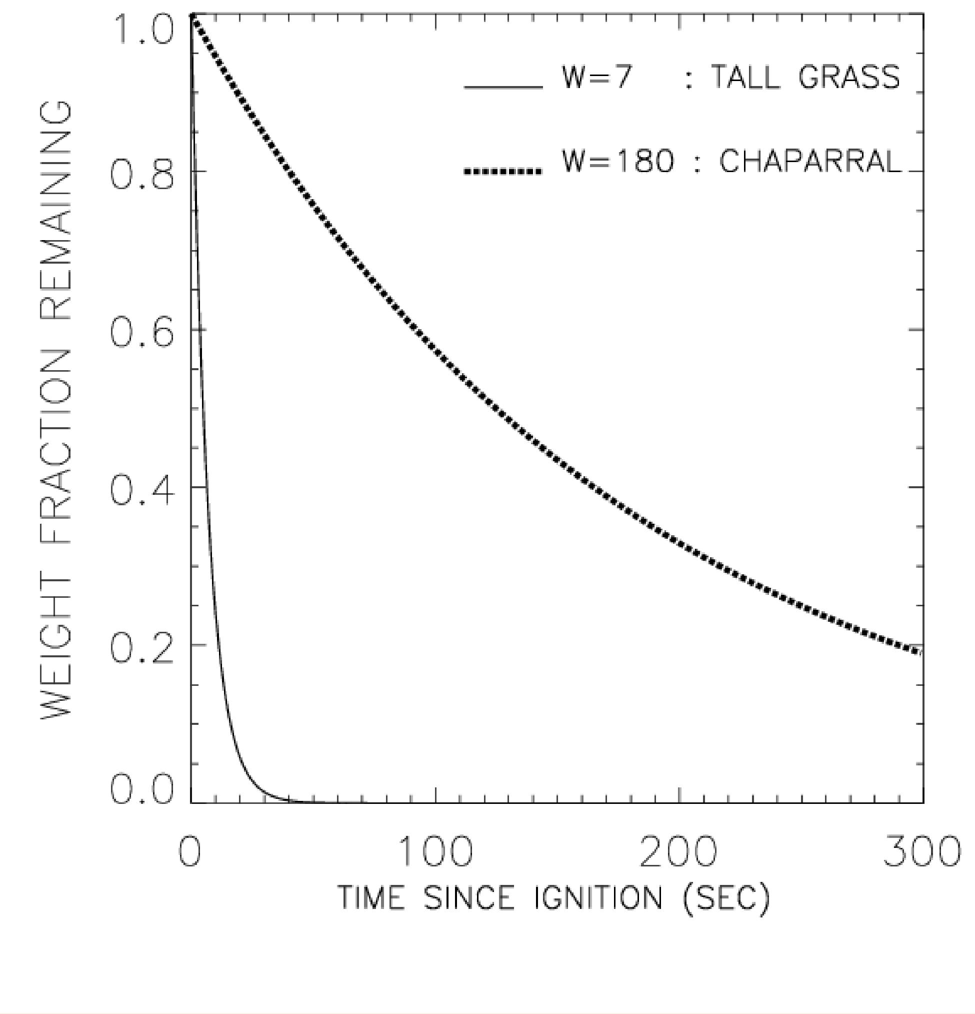
1. **Surface fire**
   - Spread of "flaming front" depends on wind, fuel, and slope. Based on Rothermel (1972) semi-empirical equations.
   - Post-frontal heat/water vapor release
   - Tracers define interface between burning and unburning regions
   - Fire line shape evolves naturally
   - Fuel can be heterogenous, can change any property

2. **Crown fire**
   - If the surface fire produces enough heat, it heats, dries, and ignites the tree canopy.

3. **Heat, water vapor, and smoke fluxes released by fire into atmosphere**


# Mass loss rate

An approximation to the BURNUP (Albini and Reinhardt) algorithm treats the rate of mass loss due to burning for fuel of different types and sizes.

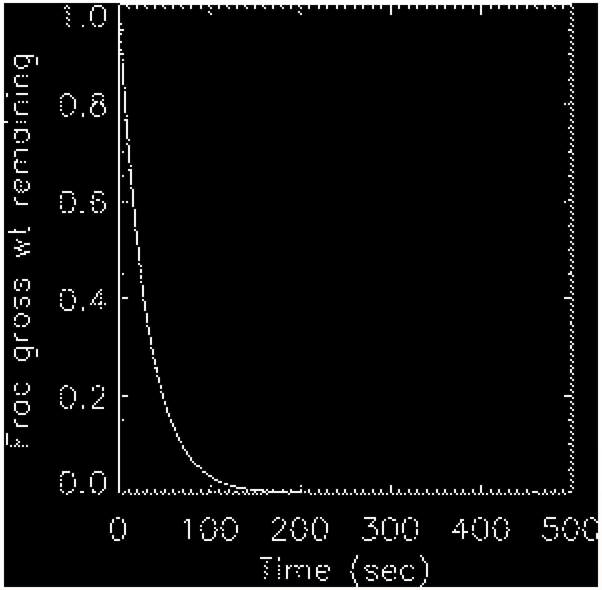


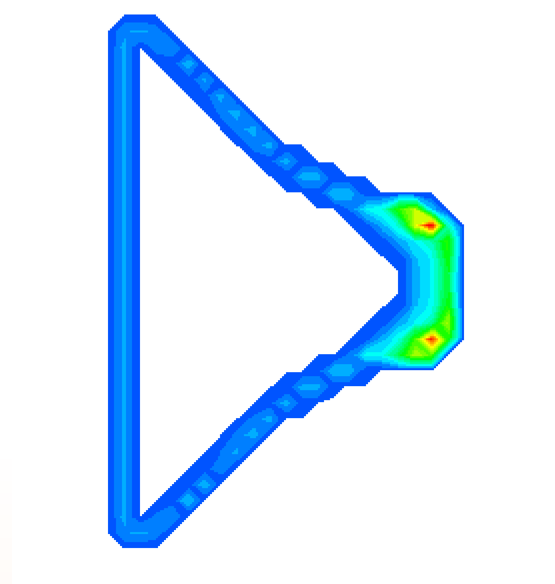
# Fraction fuel remaining with time

Heat flux (kW/m²)

Grass

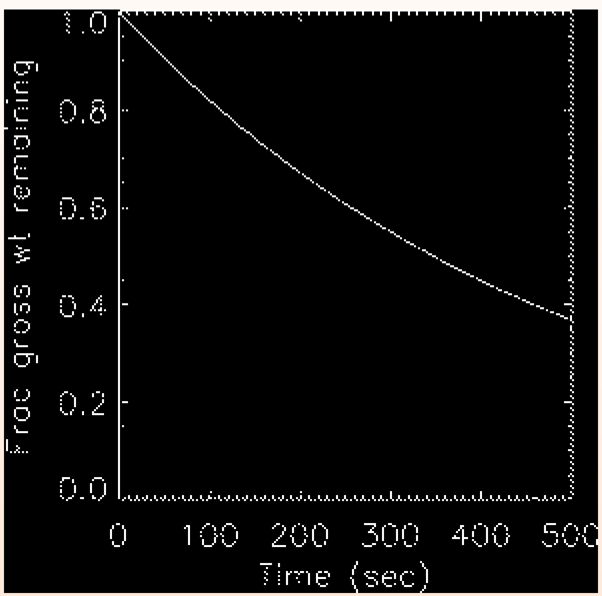
W=30

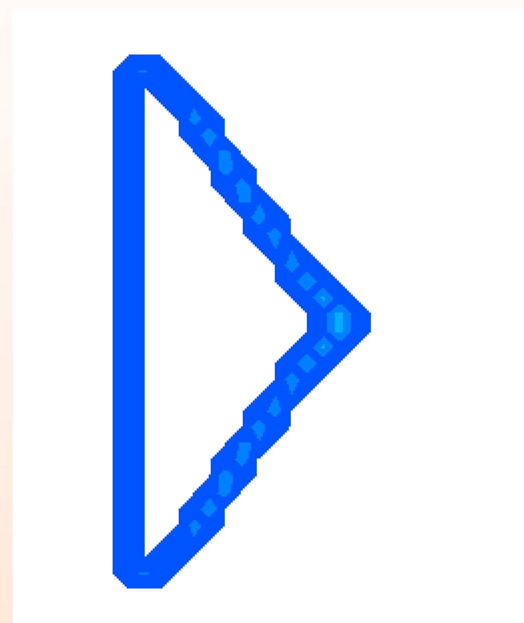


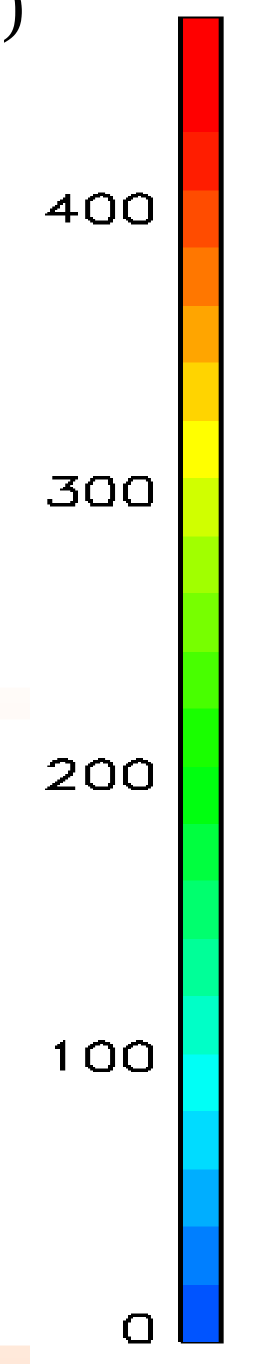



Woody fuel mixture

W=500





# The “Universal” Fire shape

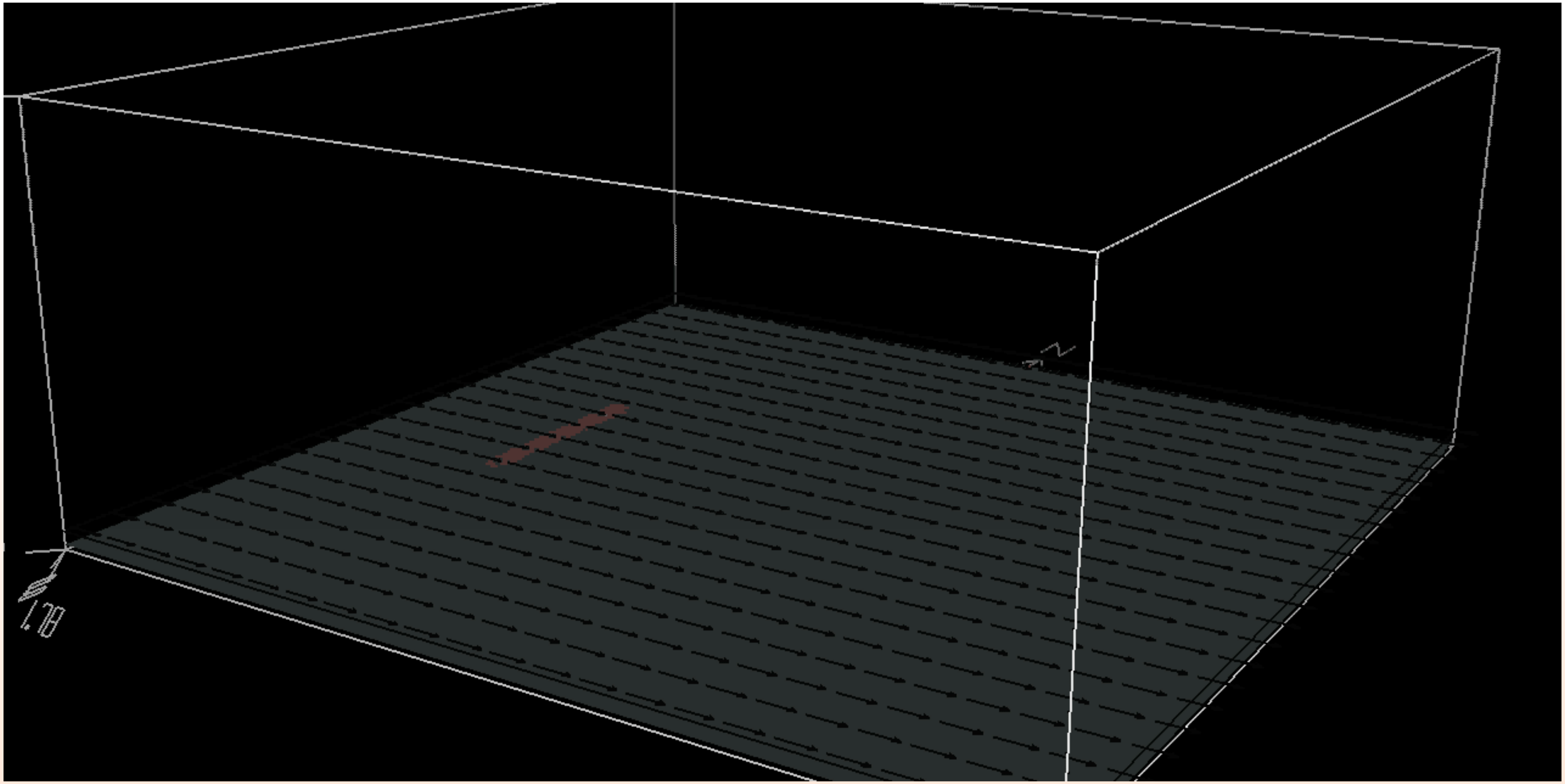
Photo courtesy Ian Knight, CSIRO

The head (the flaming front), flanks, and the backing region.

# The "universal" fire shape and fire whirls evolve from fire-atmosphere interactions.

Field: smoke

Arrows: strength and direction of winds near ground level



# Landscale-scale case studies

# 1. Big Elk Fire, CO-ARF-238 July 17–23, 2002

## “Simple” Case study

- “Simple” weather & airflow regime
- “Simple” fuel distribution

# Big Elk (cont.)

Photo courtesy of Kelly Close

# Configuration for a research problem

## 6 nested domains ( $10^6$-$10^7$ gridpoints):

- 10 km, 3.3 km, 1.1 km, 367 m, 122 m, 41 m horizontal atmospheric grid spacing. (Fuel grids much finer.). Time step in finest domain < 1 sec.

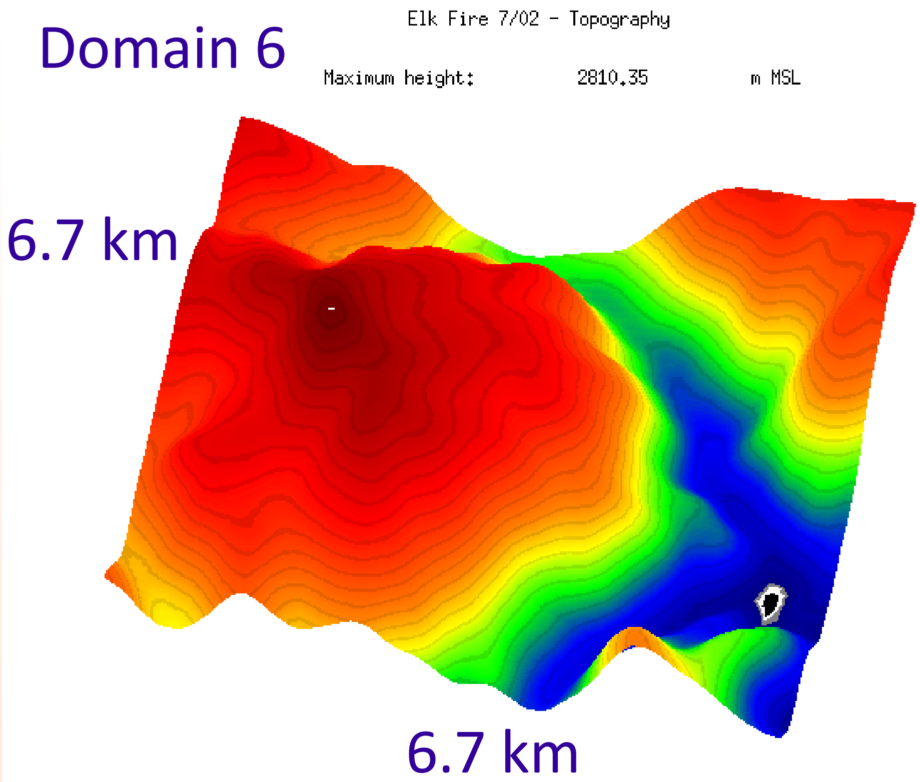
## Inputs

Atmosphere
Initialize atmosphere & provide later boundary conditions with large-scale weather forecast

Topography
US 0.33 - 3 second topography

Fuel - Surface and canopy fuels.
Mass/area
Physical characteristics

Dead (live) Fuel moisture



NESL

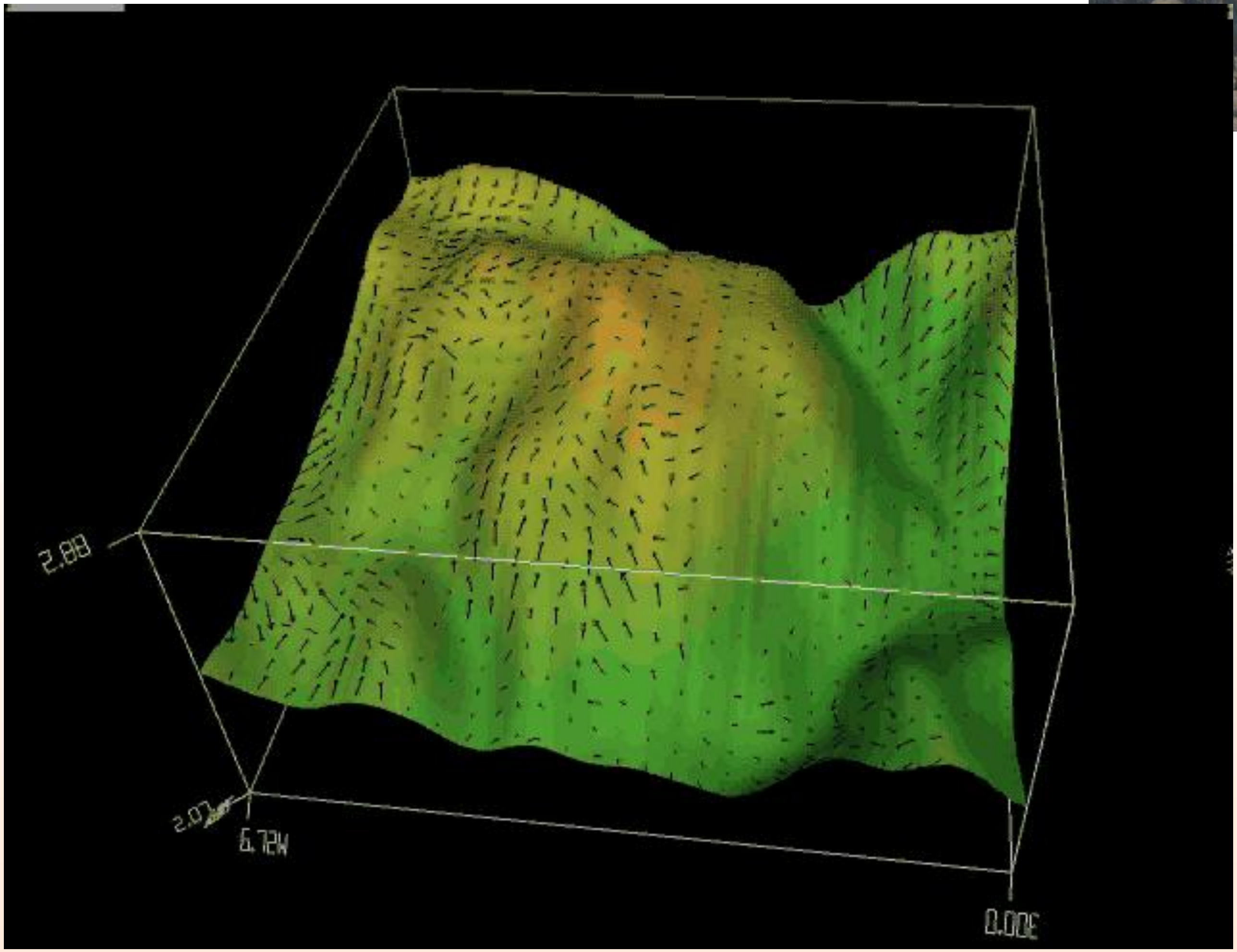
# Big Elk Fire

(4400 acres)

**Pinewood Springs, CO 17 July 2002**

N

W




4 hr simulation

Grid spacing ~50 m.

Red: Isosurface 10 $^{o}$C (18 $^{o}$F)buoyancy

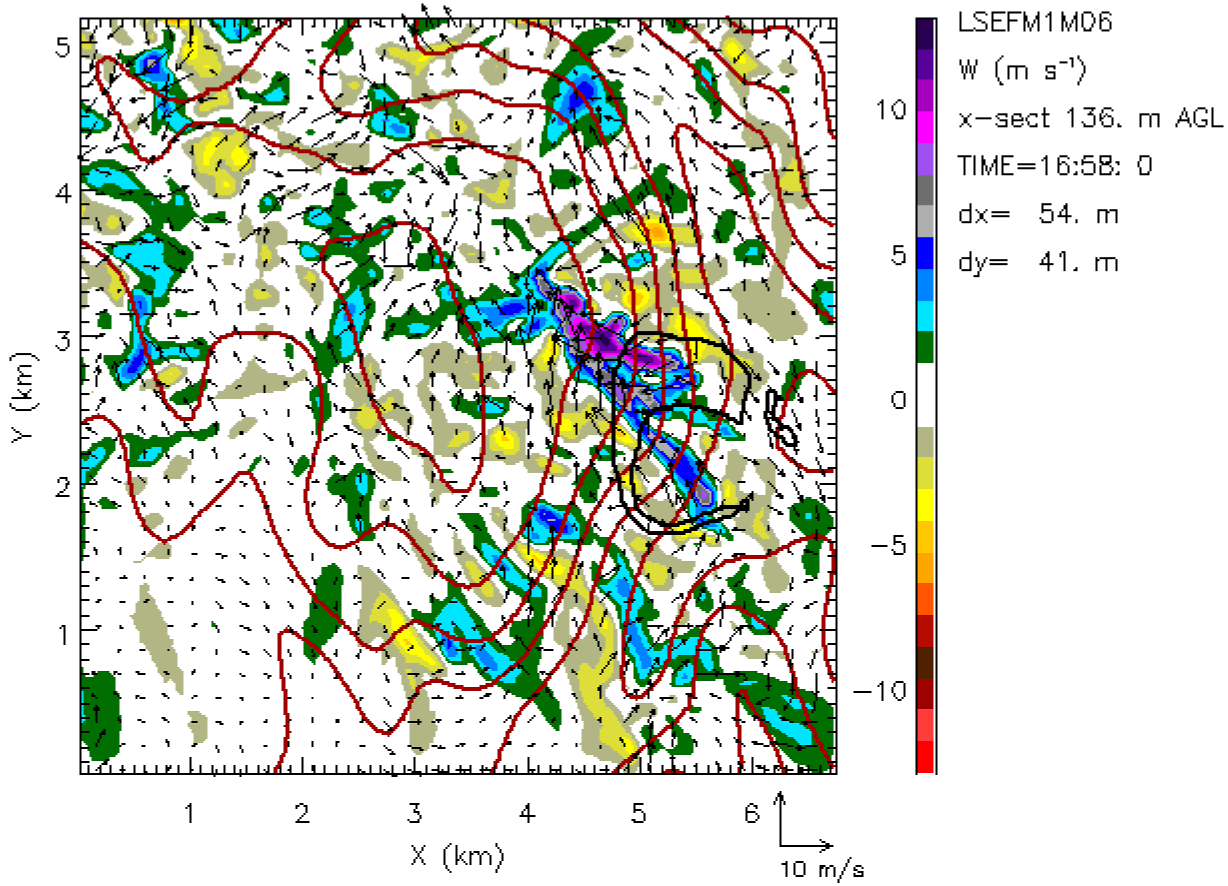
White: smoke concentration

Arrows: strength & direction of wind

Frame each 30 sec.

- Although this influence is most dramatic near the fire, model simulations show this influence can change winds by several miles per hour even miles from the fire.

# [With fire] – [Without fire]



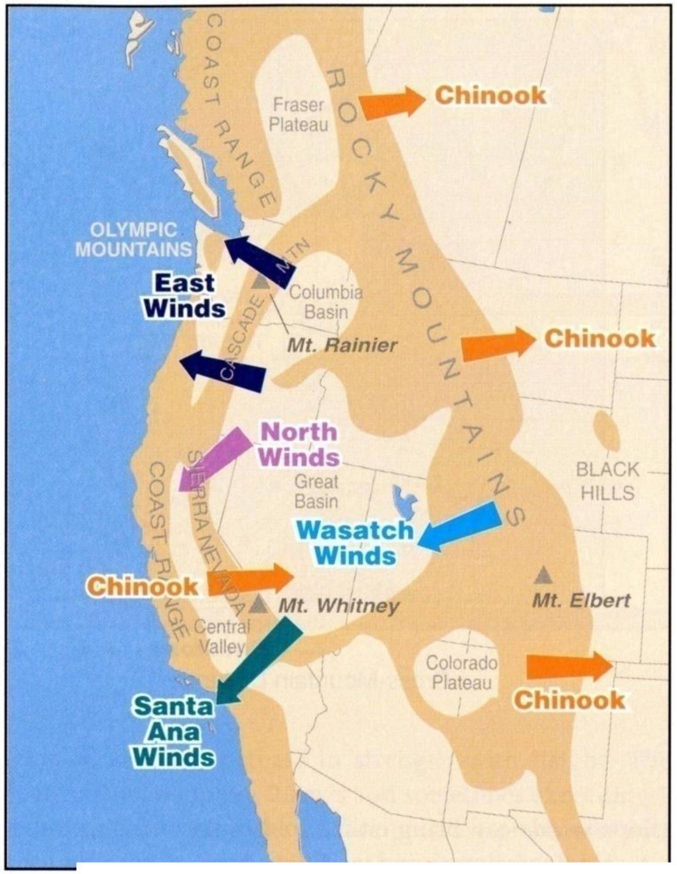
NESL

# 2. Esperanza Wildfire


- Collaborators: Phil Riggan, Francis Fujioka, David Weise (USDA Forest Service, Riverside Fire Lab), Charles Jones (Univ. of California Santa Barbara)

# Santa Ana Winds & Wildfires that occur during them

- Complex meteorology
- Complex fuels
- Complex terrain






# Santa Ana Winds

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Figure 10.15 Santa Ana winds blow out of the Mojave Desert through the Santa Clara River Valley and through Cajon and Banning Passes toward the Pacific Ocean. Wildfires are very difficult to control when these strong, gusty, dry winds are at their strongest. (Adapted from Rosenthal, 1972)

# Esperanza Fire Overview

- Ignition: arson-caused wildfire on 10-26-06 at 0112 in a river wash outside Cabazon, CA (Riverside Co.)
- Burned uphill influenced by strong winds and steep slopes. Spread WSW.
- Rapid fire spread due to Santa Ana winds (E 6-10 mph, 20-25 mph gusts), 6% RH, flammable brush

Photograph courtesy of Jeff Zimmerman

# Typical study addresses the meteorological factors, fire behavior, and interactions leading to the observed phenomena in the first day of the fire

- Experiment:
  - Start with 10-26-06 0 Z (10-25-06 1700 local time) 48-hour MM5 simulation (C. Jones, UCSB) 10 km domain
  - Interpolate to Clark-Hall weather model grid
  - Use to Initialize and update CAWFE boundary conditions
- Use CAWFE to model weather and fire
  - Nest grids, refining from 10 km -> 3.3 km -> 1.1 km -> 0.37 km
  - Simulate 17 hrs of weather + fire beginning at 10-25-06 at 2100.

# Fuel

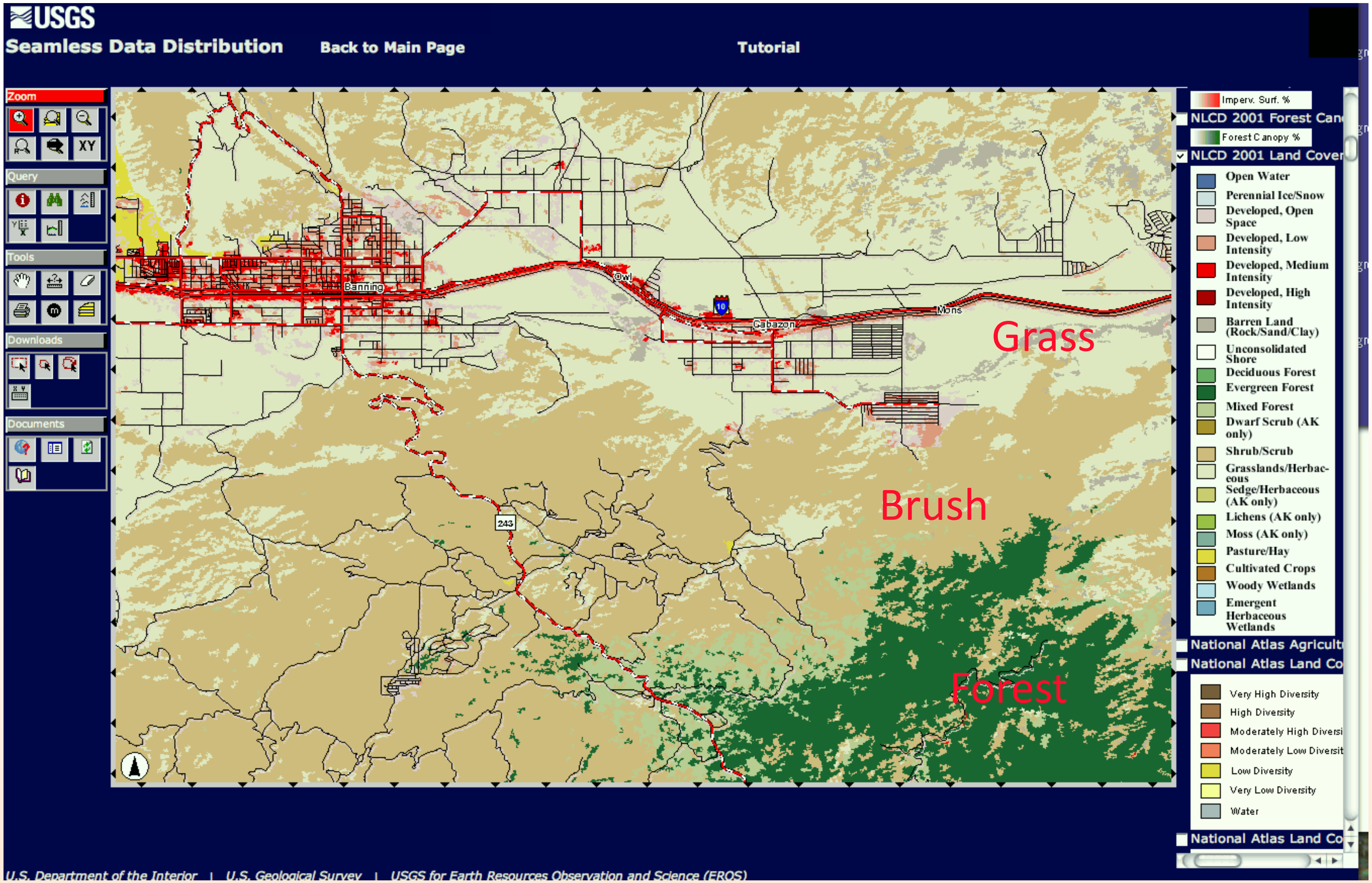
First approximation: LANDFIRE

Developing improved fuel information from pre-fire aerial

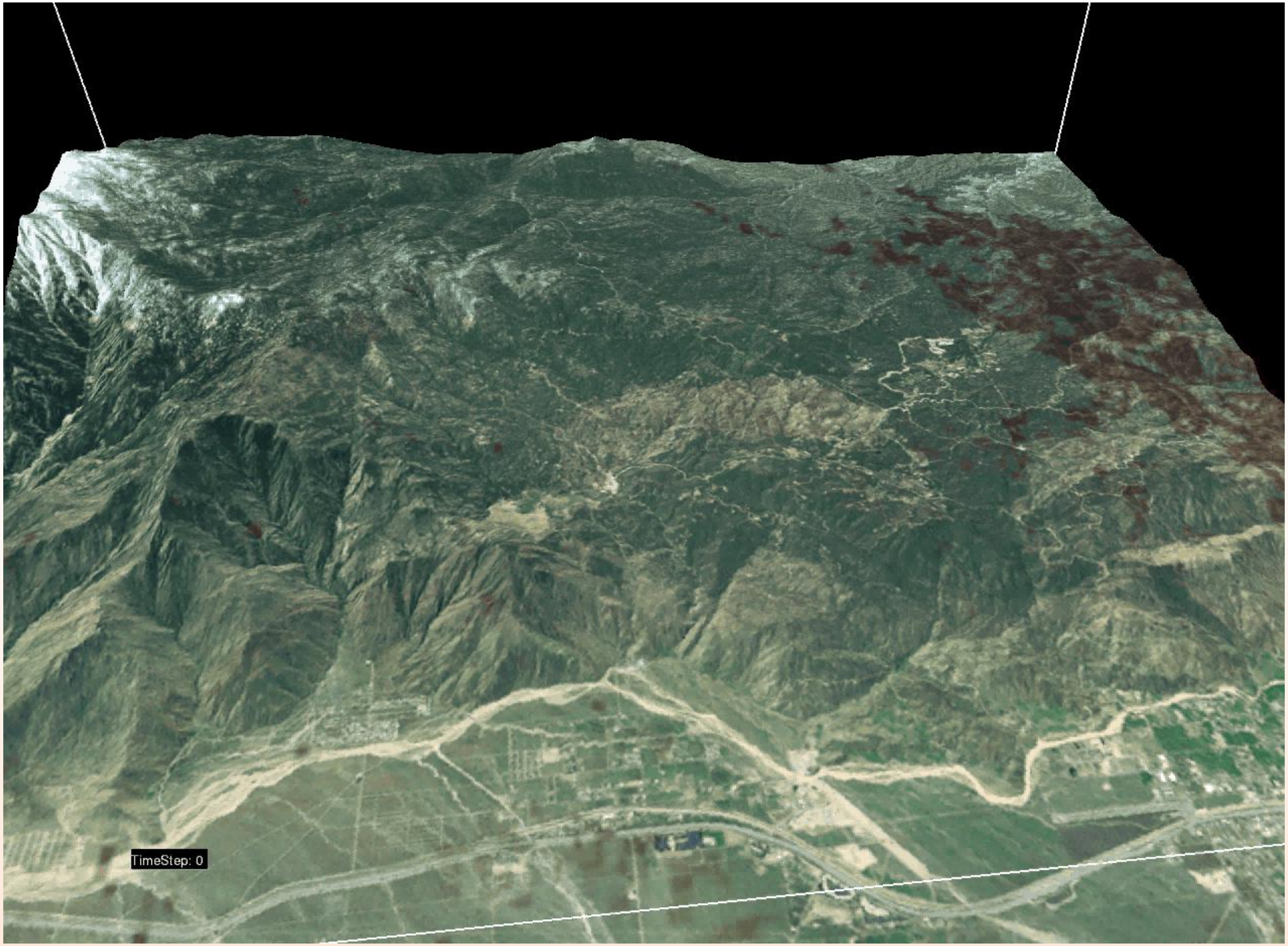
Grass: (1) short grass

Shrub: (5) mixed brush

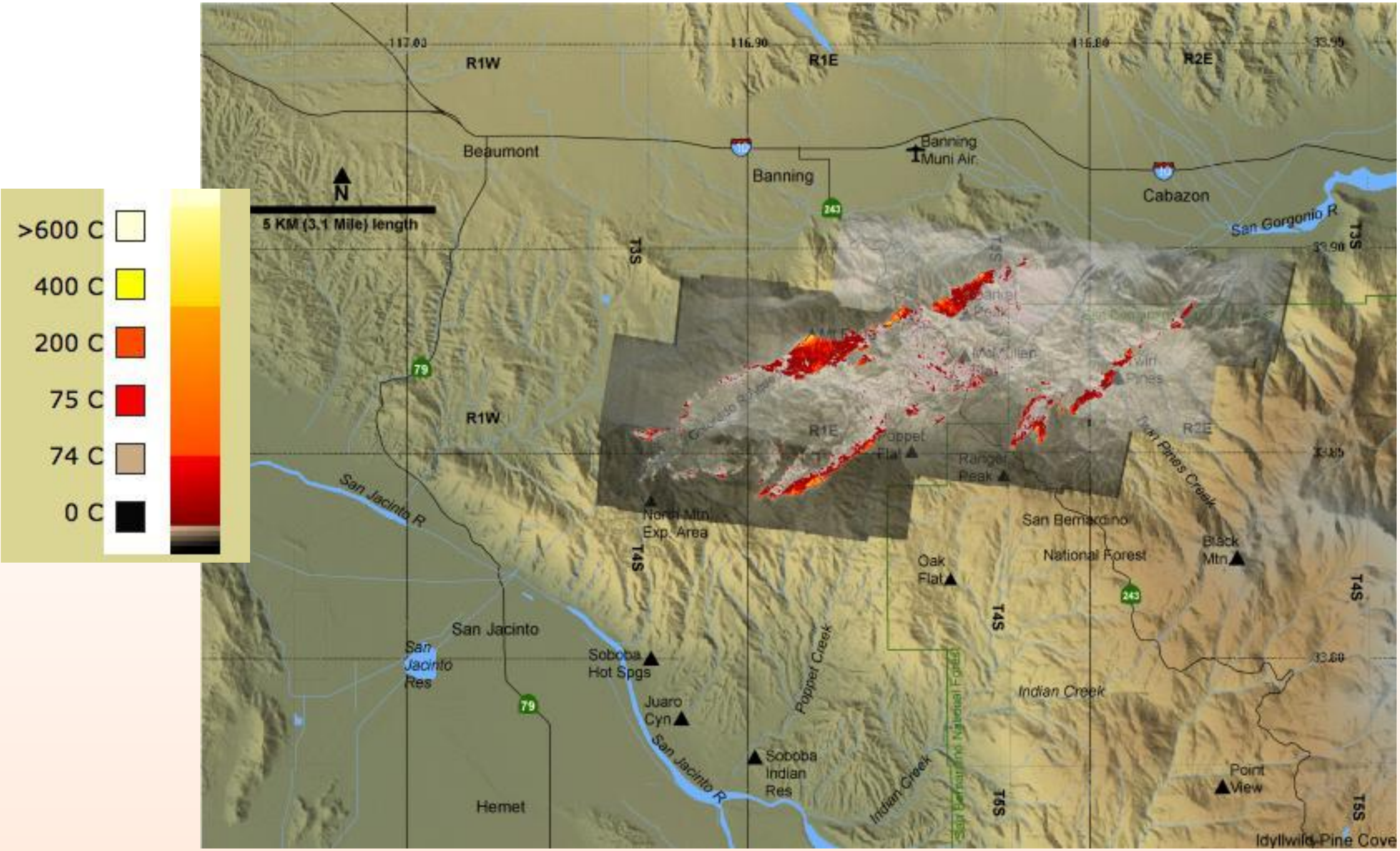
Forest: (10) heavy litter



# Fire sensible & latent heat flux and smoke 1:00 am – 9:43 am

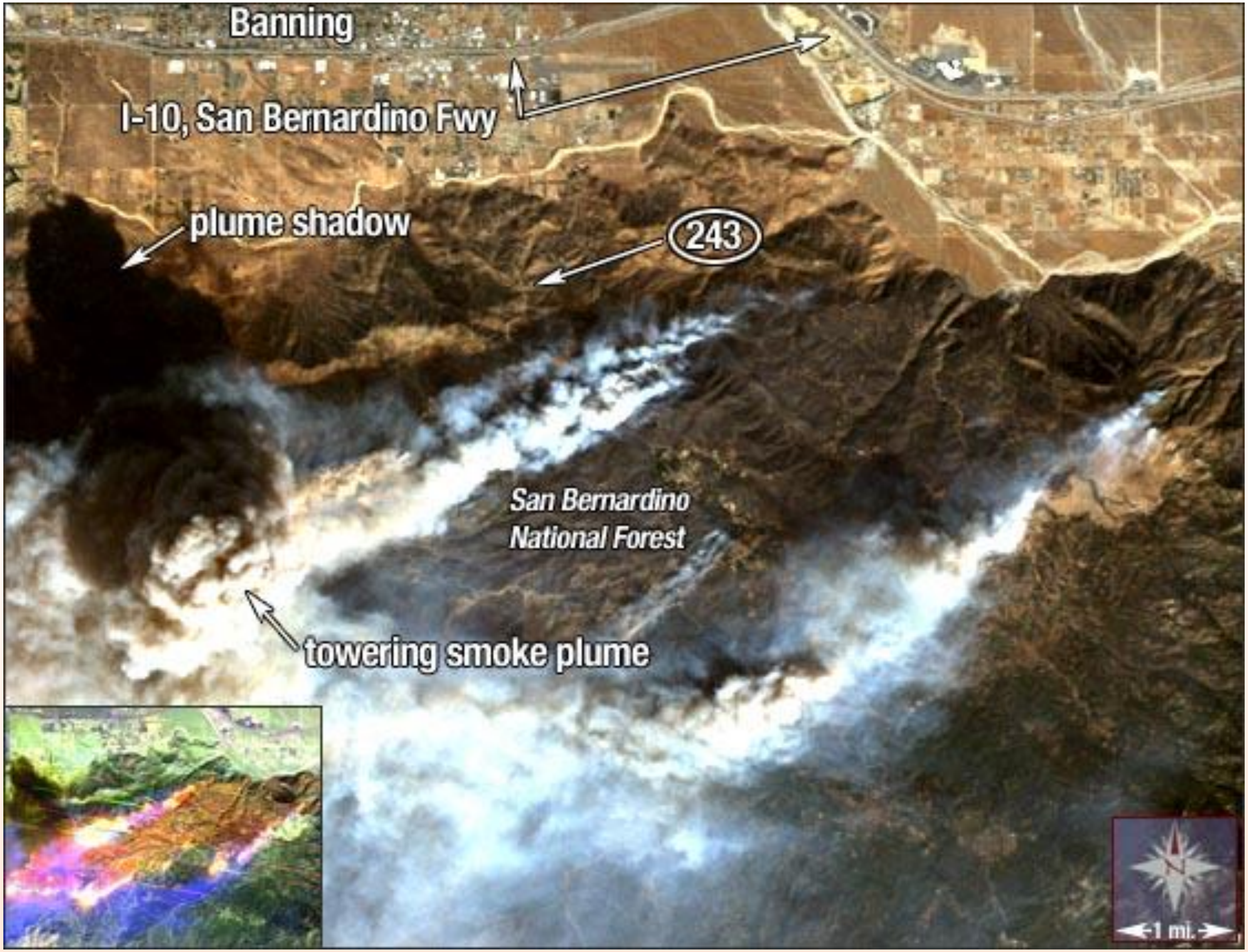


# USDA Forest Service, Riverside Fire Laboratory



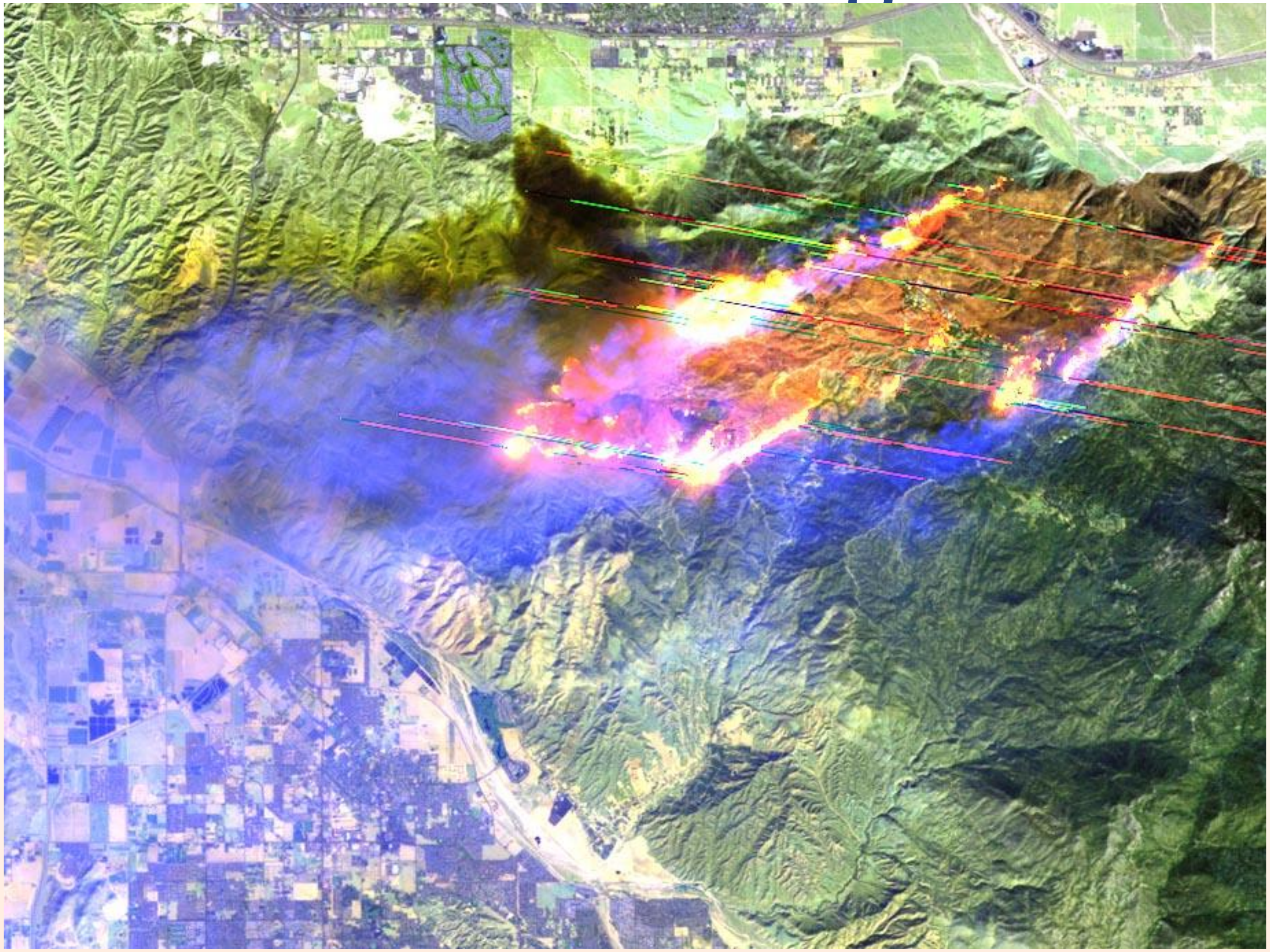

10-26-06 1117

# Landsat 5



Banning
I-10, San Bernardino Fwy
plume shadow
243
San Bernardino
National Forest
towering smoke plume
1 mi.

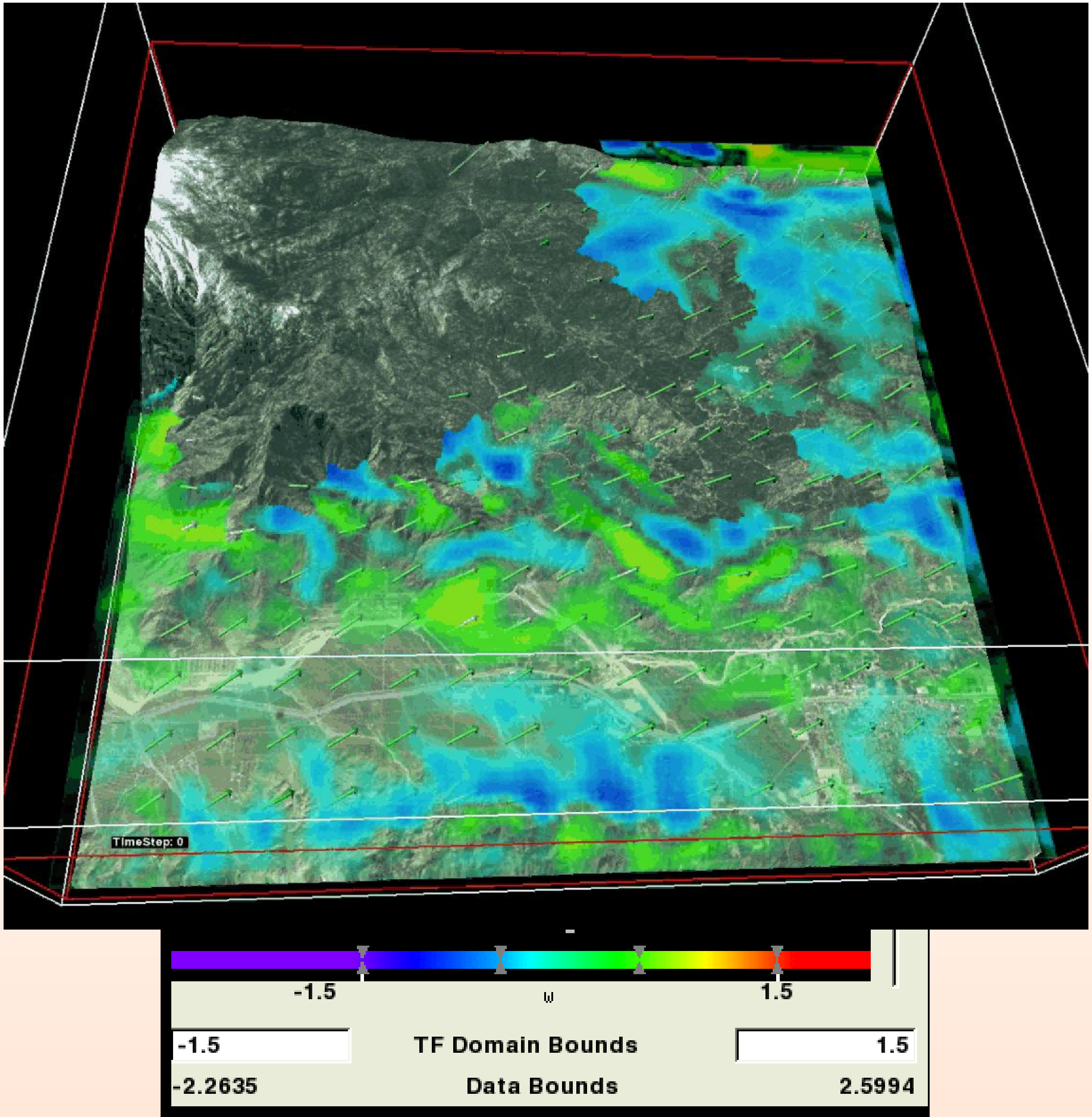
# LandSat 5 image



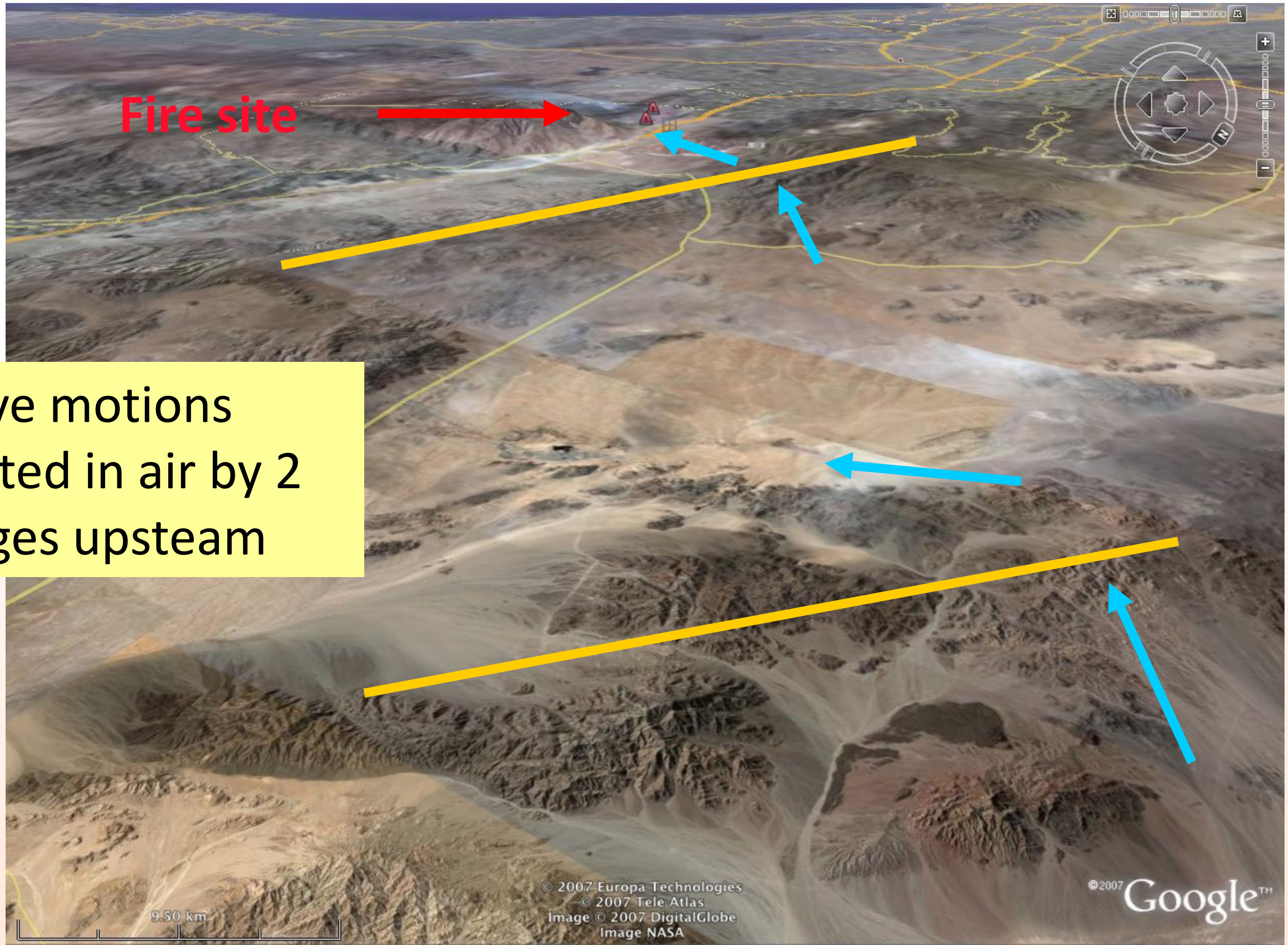
False color composite

# What where the winds near the fire?

## Fire heat flux and wind at 1500 m MSL



# Why so complex?  Let’s back upwind…




Wave motions excited in air by 2 ranges upsteam

# WRF-Fire

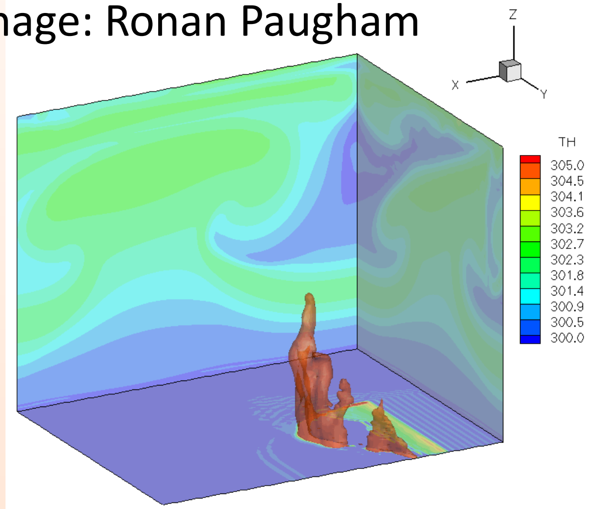
## A module to enable simulations of wildland fire behavior and interactions with weather

- **Purpose:** Develop, maintain & test a *public domain* wildland fire module for use with WRF (Weather Research and Forecasting model) that simulates wildland fire behavior over prescribed and landscape-scale fires. Why?
  - Understand 2-way interactions between 4-D weather & wildland fires that influence fire behavior and growth
  - Foundation for completely *on-line* simulation of fire plumes, emissions, transport, and (when linked to WRF-Chem) chemical evolution

- **Status: WRF-Fire module and documentation released in WRF 3.2, April 2010.**

J. L. Coen, J. D. Beezley, M. Cameron, J. Mandel, J.Michalakes, E.G. Patton, K.Yedinak, in preparation.
J. Mandel, J. Beezley, J. L. Coen, and M. Kim , 2009: Data Assimilation for Wildland Fires Ensemble Kalman filters in coupled atmosphere-surface models, IEEE Magazine.

Image: Ronan Paugham



# Sensitivity studies

- Study the sensitivity of simulated fire characteristics such as *perimeter shape, intensity, and rate of spread* to external factors known to influence fires such as *fuel characteristics, wind, and terrain slope*. Using theoretical environmental vertical profiles, experiments vary these external variables
- Results:
  - simulated fires evolve into the observed bowed shape as a result of fire-atmosphere feedbacks that establish the flow in and near fires.
  - Coupled model reproduces recognized differences in fire shapes and head intensity between flashy grass fuel, shrub surface fuel, and forest litter types.
  - Coupled model reproduces the observed tendency of heavy, dry fuels in strong winds on steeper slopes to lead to faster moving fires.

J. L. Coen, J. D. Beezley, M. Cameron, J. Mandel, J.Michalakes, E.G. Patton, K.Yedinak, in preparation.

# Applications to Biomass Emissions

# WRF + WRF-Chem + WRF- Fire (for future work)

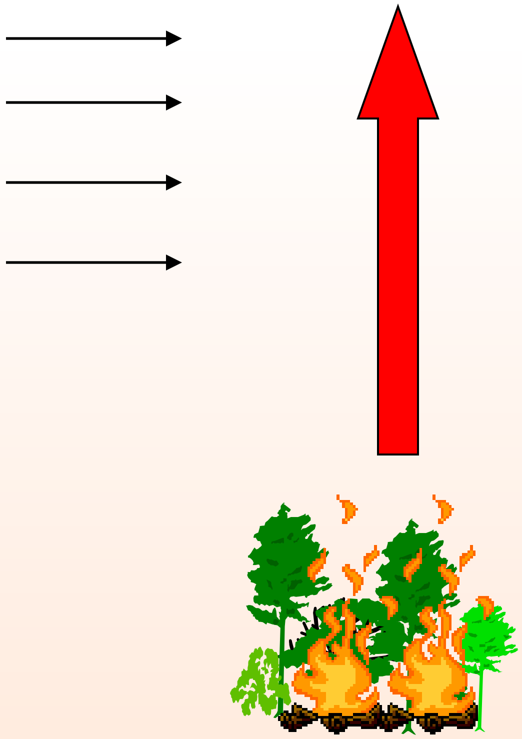
GOALS:

- Simultaneous modeling of meteorology, fire, and chemistry
- Community tool with research and operational capabilities
- Accurate spatial distribution of fire emissions into the atmosphere
- Better temporal and spatial distribution of fire emissions?
  - Smoldering vs. flaming

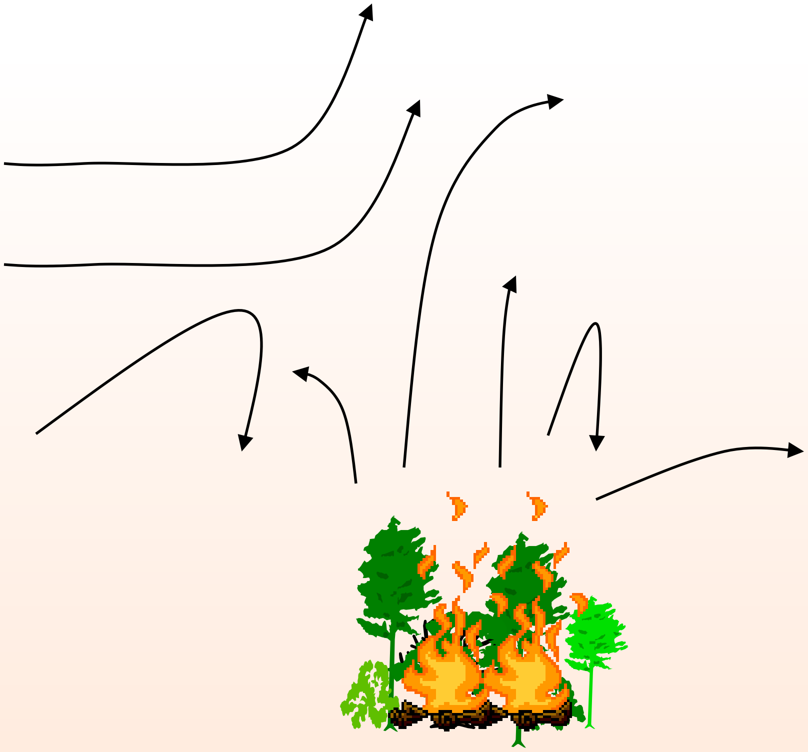
G. Pfister, C. Wiedinmyer, J. Coen, **Your Name Here?**

# WRF + WRF-Chem + WRF-Fire Fire

**Current Modeling Framework**



**On-line fire, emissions, and atmospheric chemistry modeling framework**



# Coupling with WRF-Chem

- Naturally incorporate vertical transport
- Include impact of fire evolution/intensity on emissions. Ultimately?
  - species composition
  - aerosol particle size
  - concentration

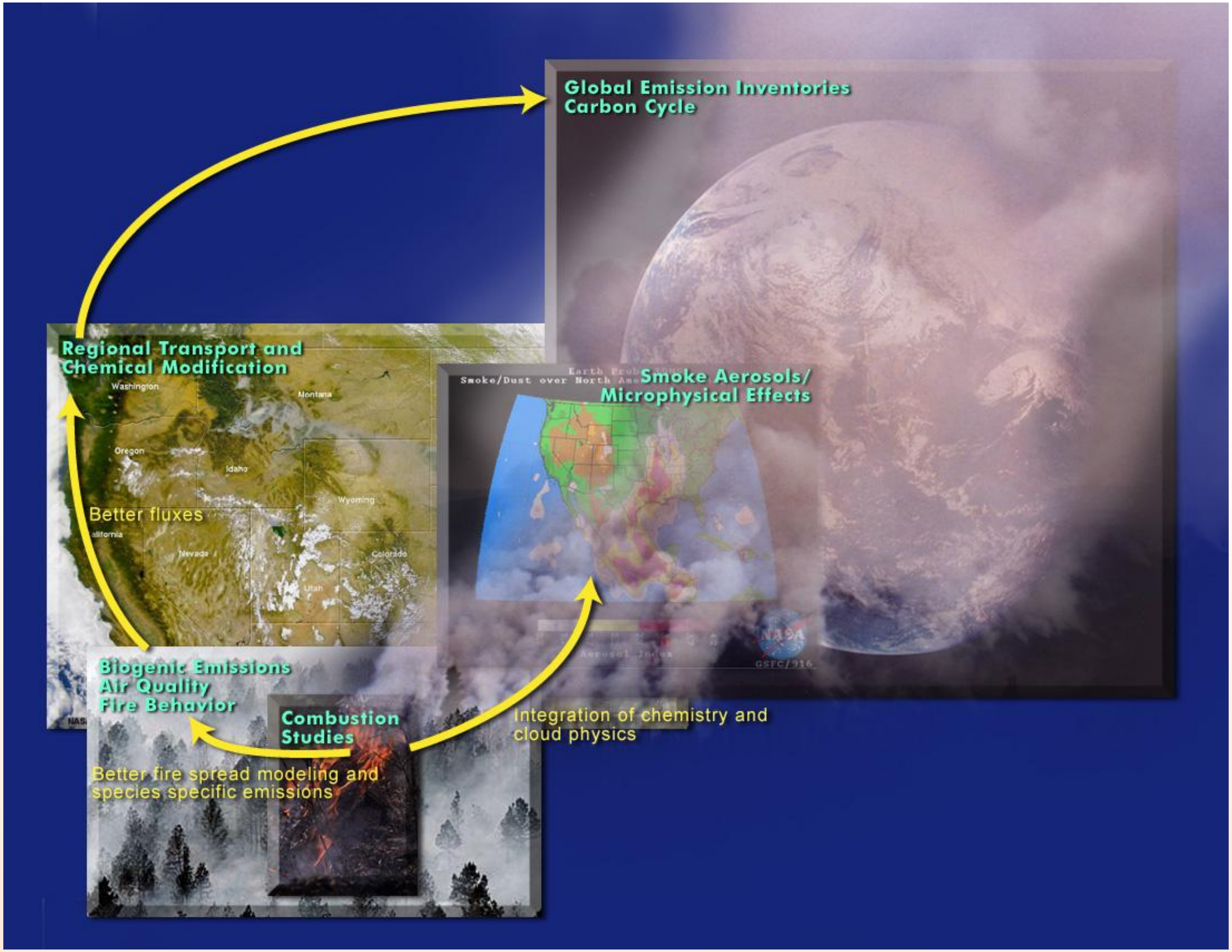
# Transport of emissions

- Obvious: static stability of the atmosphere, whether atm. + heat fluxes from fire reaches level of free convection (LFC)
- Other: Dynamics. Terrain effects. Spatial variability across a fire.

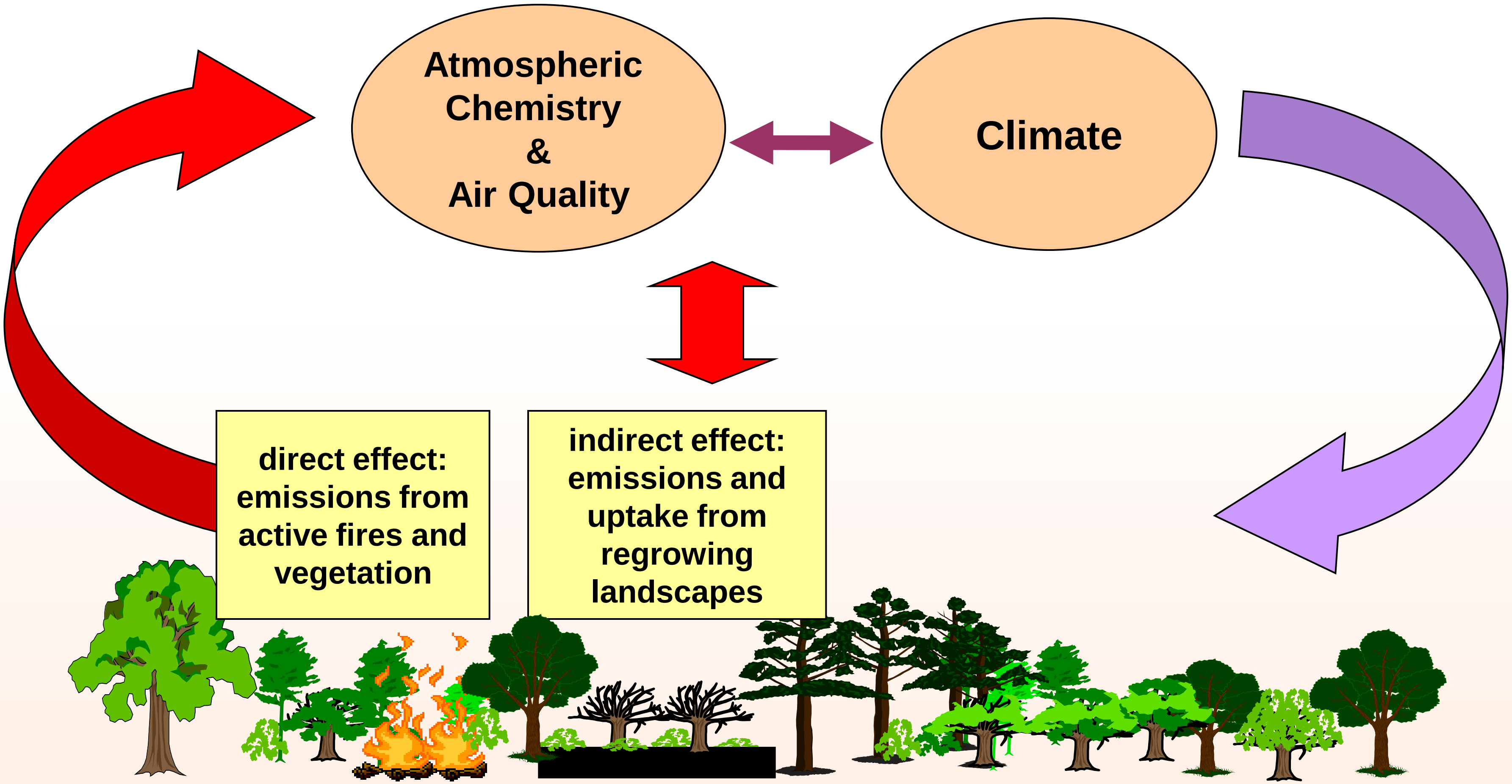

# LINGERING ISSUES

- Tough problem.  Challenges include all those of weather modeling + fire behavior + chemistry emissions issues
  - Modeling/Forecasting limitations to predictability
  - physical processes that span a vast range of scales,
  - processes such as spotting that cannot be modeled deterministically, estimating the consequences of uncertainty,
  - difficulty of gathering pertinent data for verification and initialization in a dangerous environment

# CAN THESE BE USED AS A 'PHYSICALLY CONSISTENT' CHECK ON LARGER-SCALE MODELS?



# Big Picture




Modeling and Observational Framework
-better understand emissions from fires and living vegetation
-feedbacks between the atmosphere and the biosphere

# For more information:

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*NCAR is sponsored by the National Science Foundation*

Photos: http://zimmermanmedia.com

# Thank You

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**To provide facility support to the wider community; and,**
**To apply the results to benefit society.**

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