WRF-Fire:
A physics package for modeling wildland fires

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Introduction

- **WRF-Fire is a physics package within WRF ARW that allows users to model the growth of a wildland fire**
- **Fire responds to environmental conditions:**
  - terrain slope, fuel characteristics, and atmospheric conditions (winds)
- **2-way coupling between the fire behavior and the atmospheric environment**
  - The latent and sensible heat released by the fire alter the atmosphere surrounding it, which in turn affect winds that determine the direction and rate of spread of the fire - *i.e*. the fire 'creates its own weather'.
- **It was first released in Version 3.2 (April 2010).**
- **Details for use are in *WRF ARW User's Guide Appendix A***
  - *Paper:* Coen, J. L., M. Cameron, J. Michalakes, E. G. Patton, P. J. Riggan, and K. M. Yedinak, 2013: WRF-Fire: Coupled Weather-Wildland Fire Modeling with the Weather Research and Forecasting Model. J. Appl. Meteor. Climatol., 52:16-38.
  - Contributions to WRF-Fire came from numerous people at NCAR, the U.S.D.A. Forest Service, the Australian Bureau of Meteorology, and the Univ. of Colorado at Denver.

3 Environmental Factors that affect Wildland Fire Behavior

Fuel

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

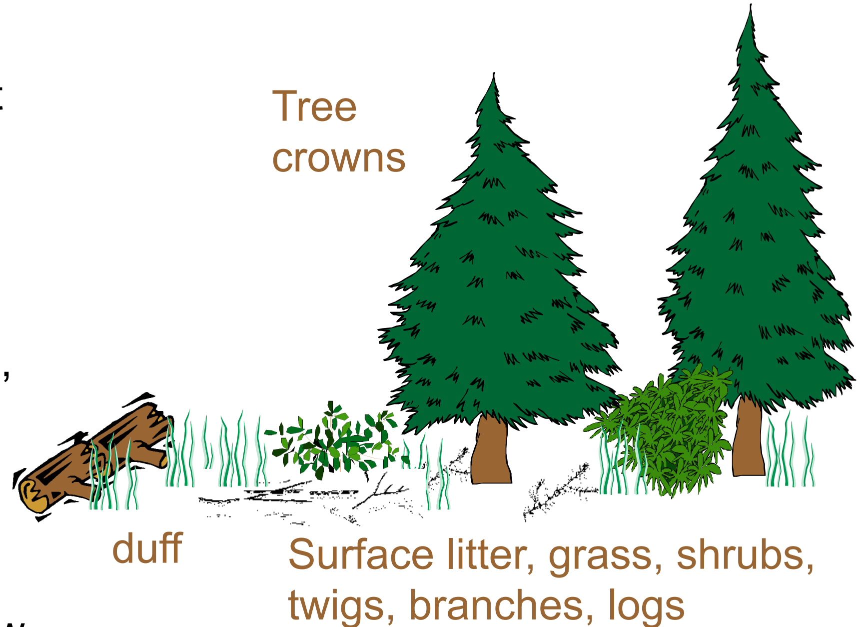
Weather

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

Coupled Weather – Wildland Fire Modeling

FIRE-WEATHER FEEDBACKS

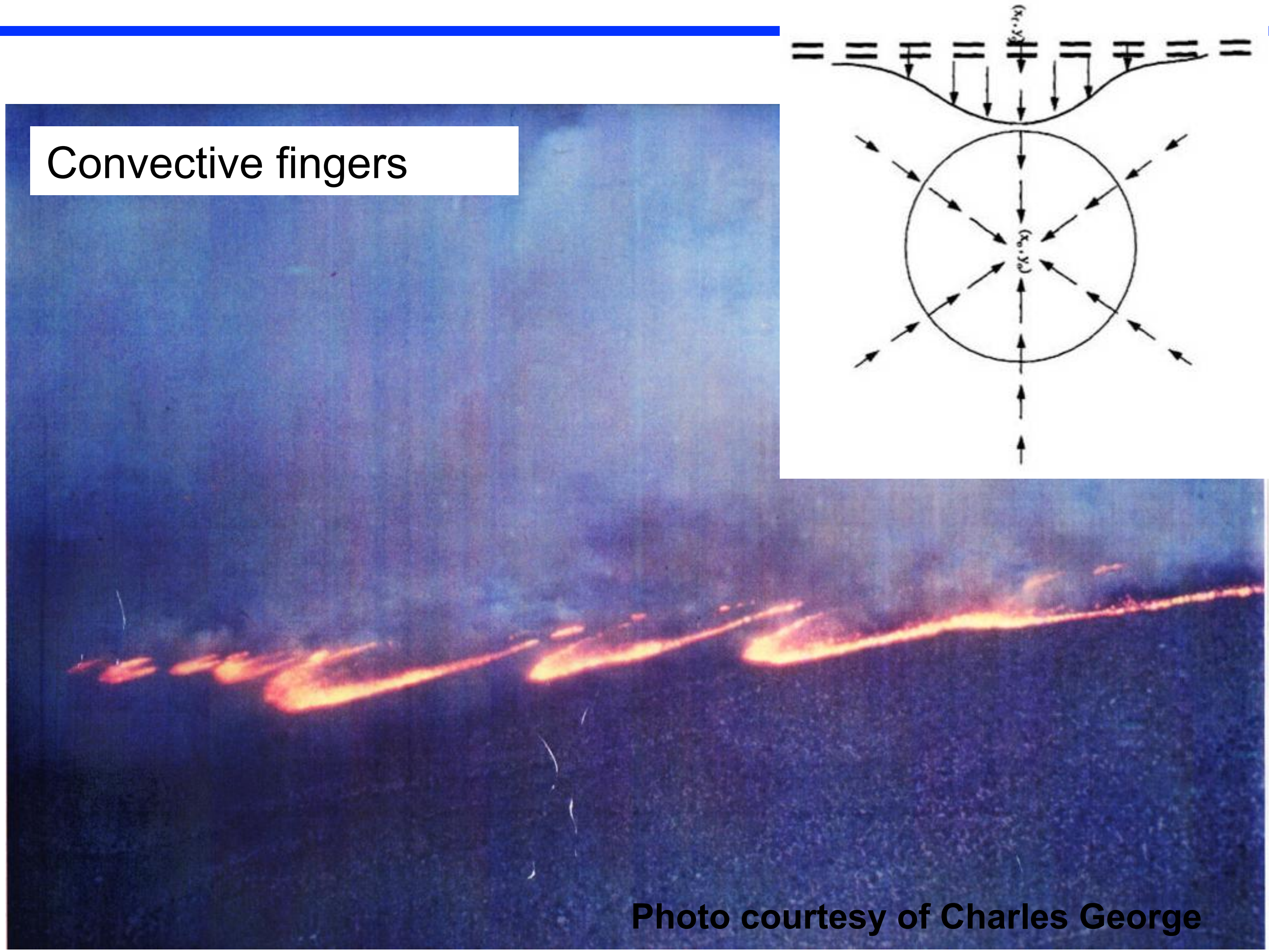
The atmosphere (i.e. wind) exerts a force on fires, directing where/how fast they spread and affects fuel properties like fuel moisture that determine whether/how intensely a fire will burn.

Sensible heat flux (temperature) Latent heat flux (water vapor), [smoke]

Wind speed and direction, humidity

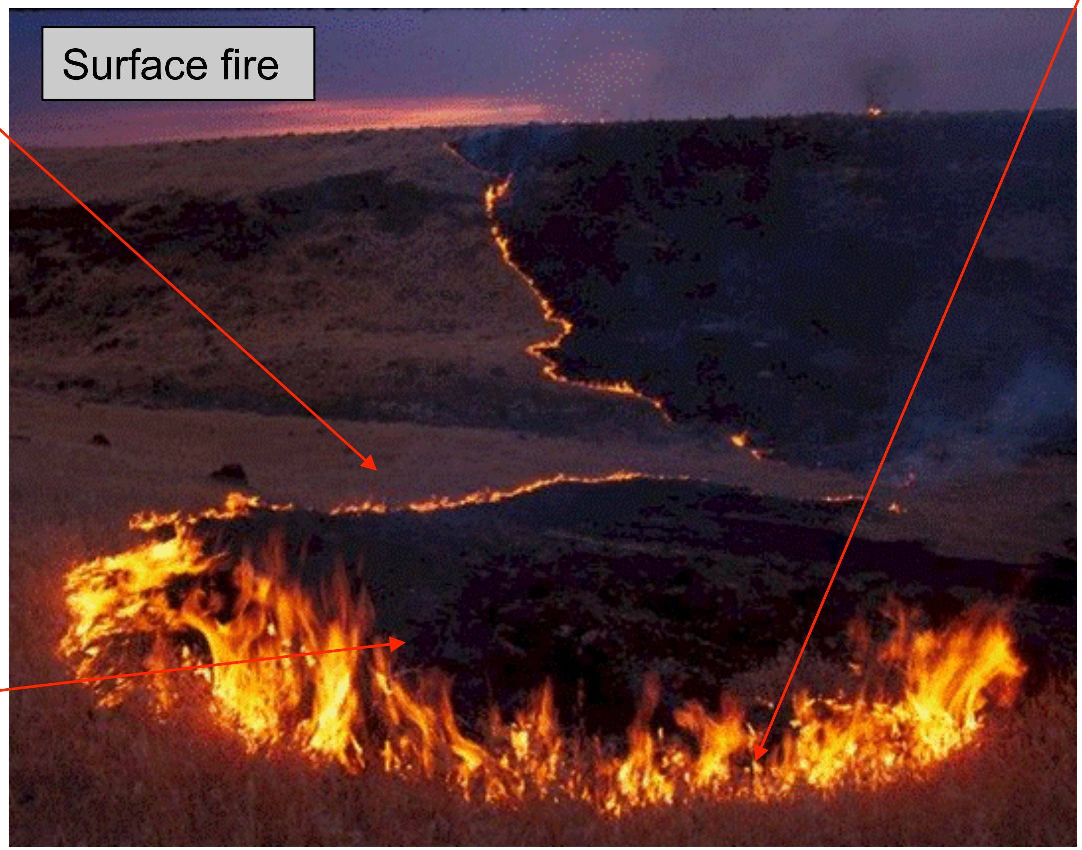
Fires consume fuel and release heat and water vapor into the air, causing it to rise, and changing the winds in the fire's environment.

Example: A fire phenomenon resulting from fire-weather interaction



Physical Processes

Representation of sub-atmospheric grid-scale interface between burning and unignited area



Spread rate of "flaming front" is function of wind, fuel, and slope (Rothermel (1972) semi-empirical equations).

Post-frontal heat & water vapor release

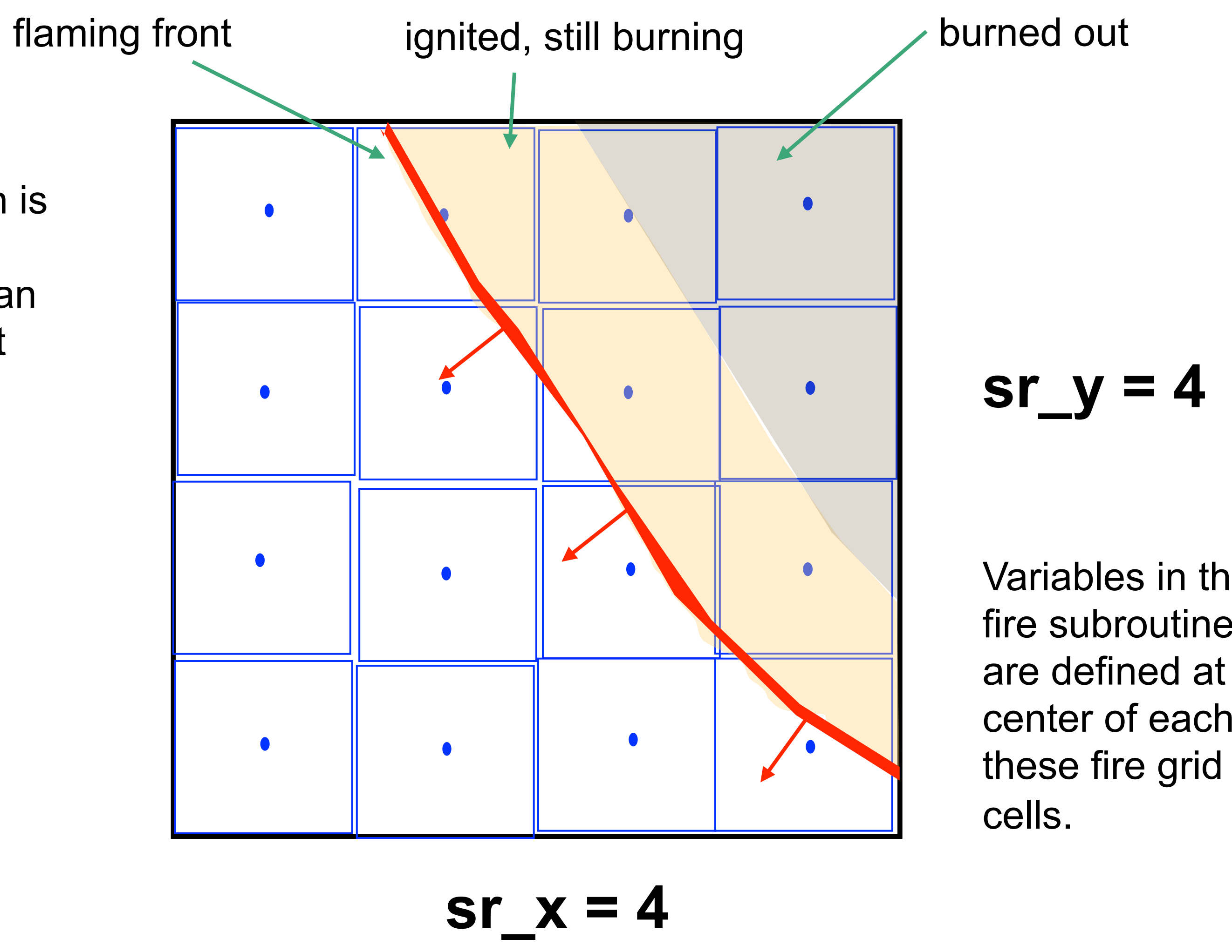
Heat, water vapor, and smoke fluxes released by simulated fire into lowest layers of atmospheric model

What do these subroutines do?

- **User specifies time, location, and shape of a fire ignition**
- **At each atmospheric time step for the innermost grid:**
  - Interpolate the near-surface winds to the fire cell grid points.
  - Calculate the rate at which the interface enclosing the burning region expands at points all along it with a semi-empirical formula (Rothermel, 1972)
  - Advance the fire front for this time step.
  - Calculate how much mass has been burned (integrated over the burning area within each fire cell) and multiply by the energy content of the fuel (J/kg) to get energy release rate (J/(s m^2), or W/m^2).
  - Sum up the heat release for all the fire cells within each atmospheric cells.
    - Sensible heat flux (temperature) – W m^{-2}
    - Latent heat flux (water vapor) - W m^{-2}
      - 56% of each cellulose cell is water
      - Fuel moisture content is the fuel absorbed between the cells
  - Distribute this as a tendency to the lowest levels of the atmospheric model
- **Return to atmospheric model**

Within each x-y atmospheric grid cell on the earth’s surface is a x-y mesh of fire grid cells

The fire mesh is sr_x by sr_y times finer than the innermost atmospheric mesh.



Variables in the fire subroutines are defined at the center of each of these fire grid cells.

Spread Rate of a Flaming Front

(Semi-empirical) Rothermel eqns (1972)

$$R = \frac{I_R \xi}{\rho_b \varepsilon Q_{ig}} (1 + \phi_w + \phi_s)$$

$\frac{I_R \xi}{\rho_b \varepsilon Q_{ig}}$: Zero-wind spread rate on flat ground

ϕ_w: wind factor

ϕ_s: slope factor

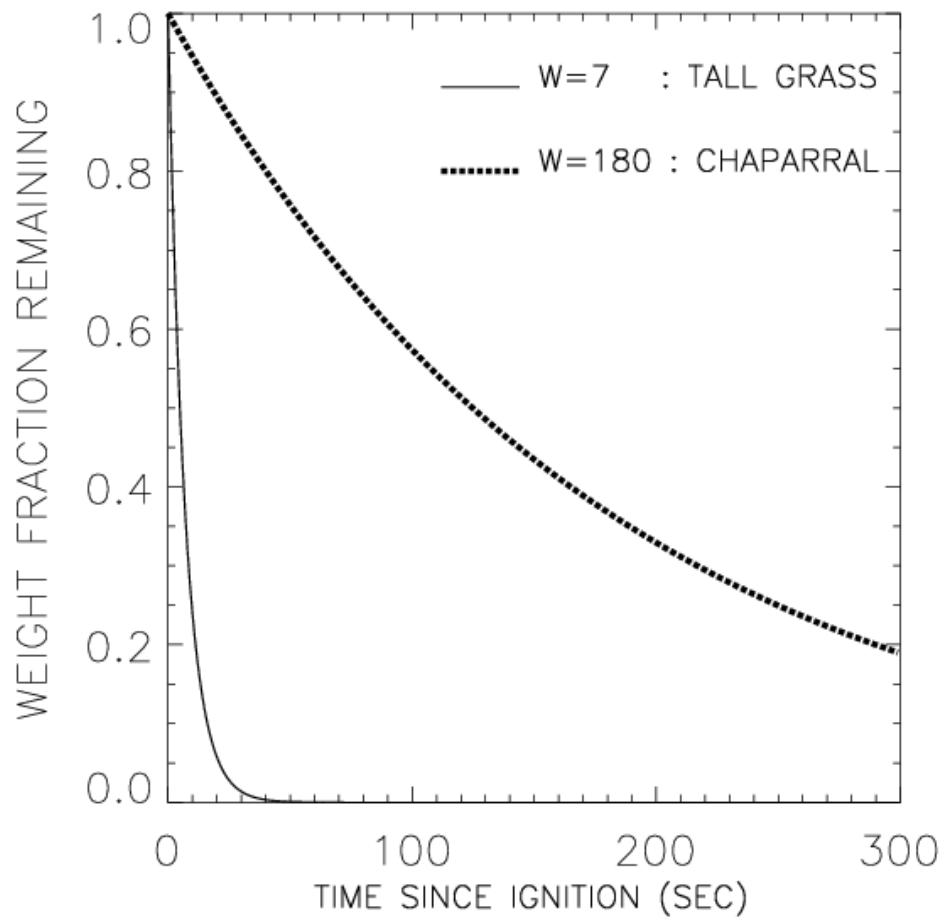
$$\frac{\text{Heat energy of fuel}}{\text{Heat required to prepare fuel \& ignite}}$$

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)

Mass loss rate after ignition

Once fuel ignites, its mass decreases. Lab experiments show that the mass decreases approximately exponentially.

An approximation to the BURNUP (Albini, 1994) algorithm treats the rate of mass loss due to burning for fuel of different types and sizes.



Reference:

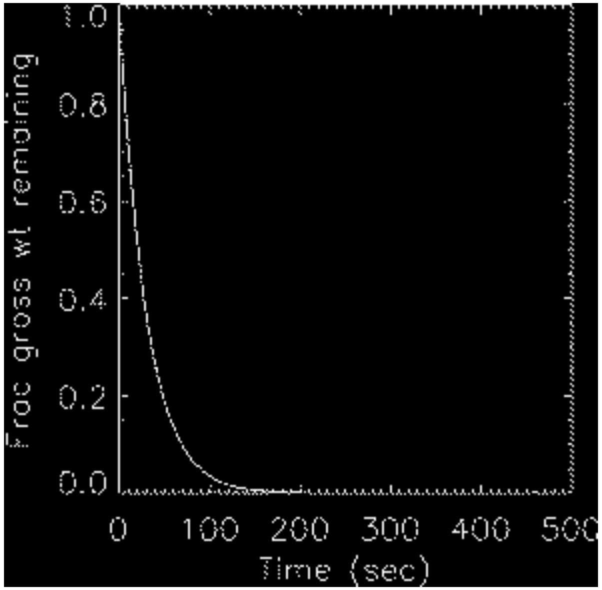
Albini FA (1994) PROGRAM BURNUP, A simulation model of the burning of large woody natural fuels. Final Report on Research Grant INT-92754-GR by U.S.F.S. to Montana State Univ., Mechanical Engineering Dept.

Fraction of fuel remaining with time

"Flashy" fuels

Grass

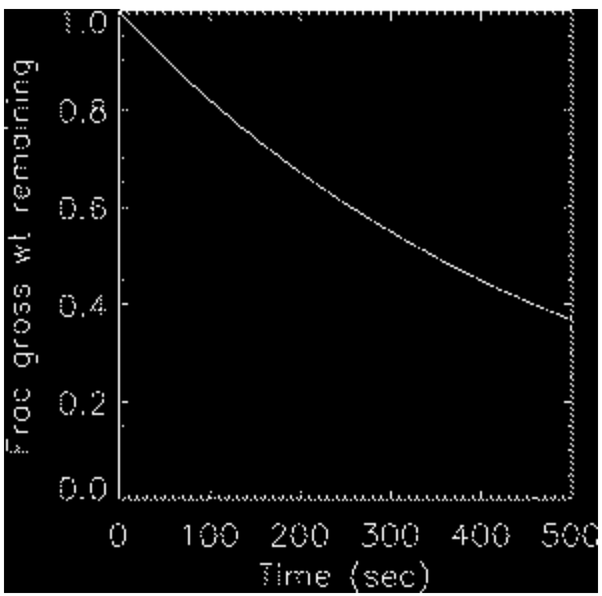
W=30 s



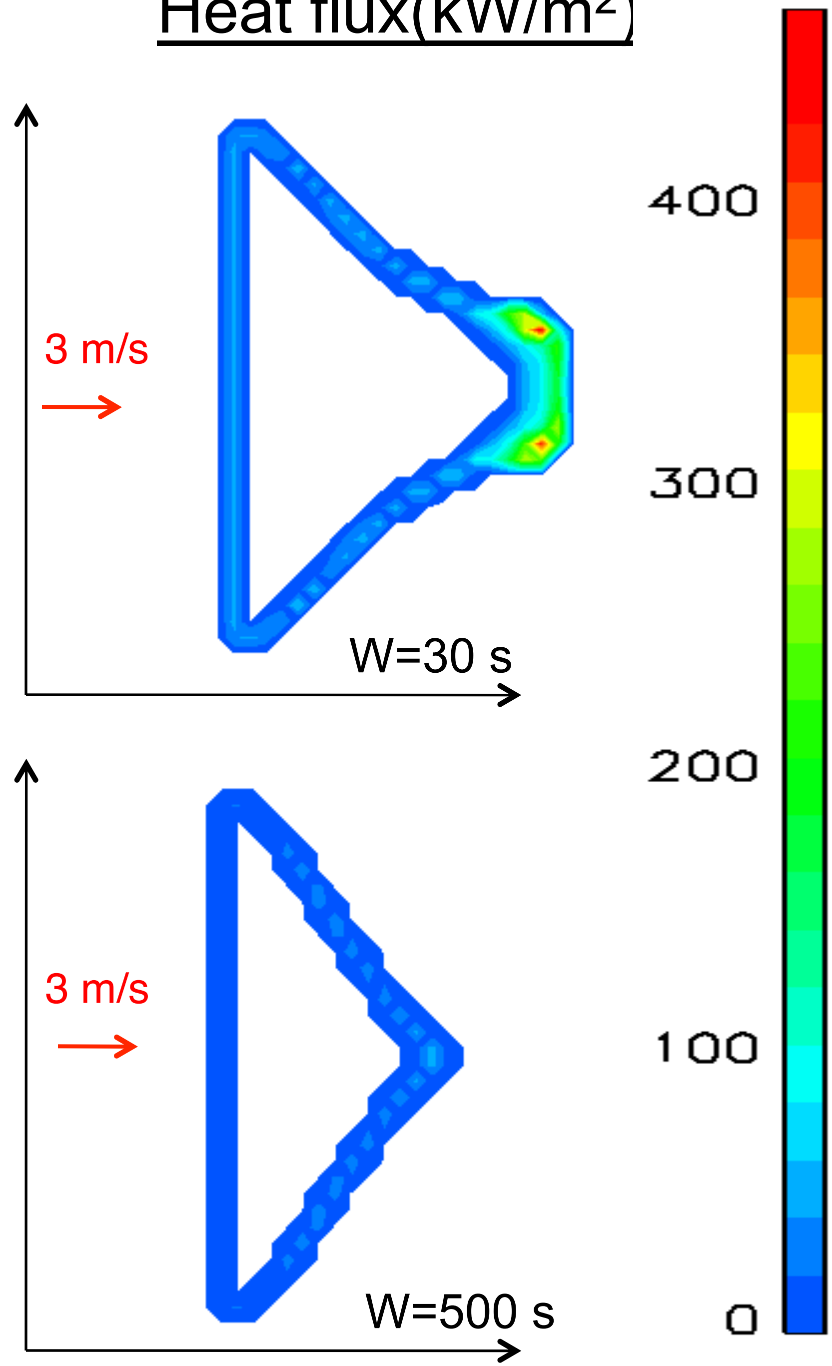
Slow-burning

Woody fuel mixture

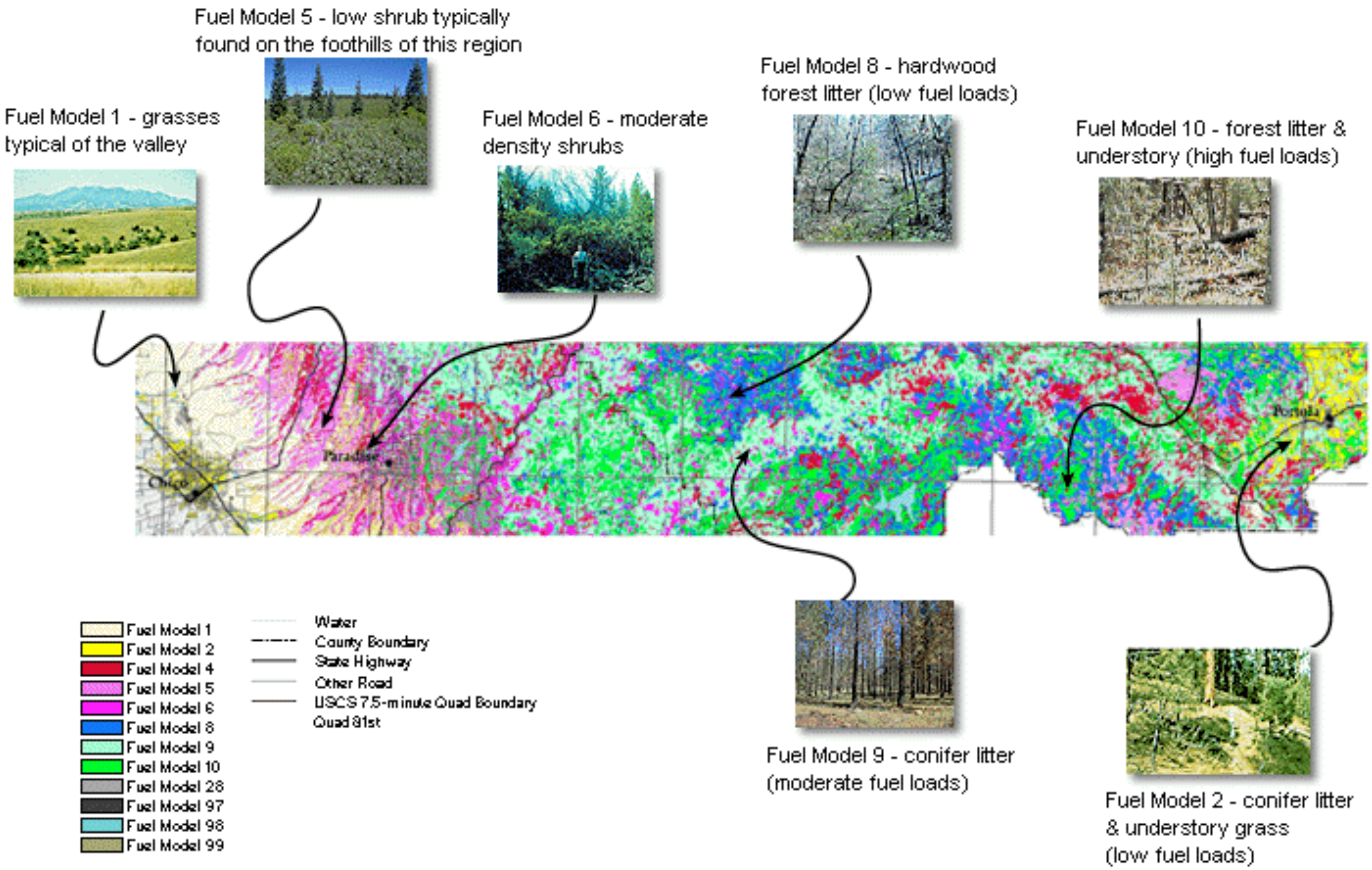
W=500 s



Heat flux(kW/m²)



A “Fuel Model” is a collection of fuel properties based on the amount, physical properties, and spatial distribution of surface fuel elements



Cross Section of Fuel Map from Northern Sacramento Valley to Portola

Image courtesy of California Division of Forestry

The most commonly used fuel classification system is the 13-category Anderson fuel model system

Table 1. — Description of fuel models used in fire behavior as documented by Albini (1976)

Fuel model	Typical fuel complex	Fuel loading 1 hour	Fuel loading 10 hours	Fuel loading 100 hours	Fuel loading Live	Fuel bed depth	Moisture of extinction dead fuels
		Tons/acre				Feet	Percent
	Grass and grass-dominated						
1	Short grass (1 foot)	0.74	0.00	0.00	0.00	1.0	12
2	Timber (grass and understory)	2.00	1.00	.50	.50	1.0	15
3	Tall grass (2.5 feet)	3.01	.00	.00	.00	2.5	25
	Chaparral and shrub fields						
4	Chaparral (6 feet)	5.01	4.01	2.00	5.01	6.0	20
5	Brush (2 feet)	1.00	.50	.00	2.00	2.0	20
6	Dormant brush, hardwood slash	1.50	2.50	2.00	.00	2.5	25
7	Southern rough	1.13	1.87	1.50	.37	2.5	40
	Timber litter						
8	Closed timber litter	1.50	1.00	2.50	0.00	0.2	30
9	Hardwood litter	2.92	41	.15	.00	.2	25
10	Timber (litter and understory)	3.01	2.00	5.01	2.00	1.0	25
	Slash						
11	Light logging slash	1.50	4.51	5.51	0.00	1.0	15
12	Medium logging slash	4.01	14.03	16.53	.00	2.3	20
13	Heavy logging slash	7.01	23.04	28.05	.00	3.0	25

Anderson, H. E. 1982. *Aids to determining fuel models for estimating fire behavior.* USDA For. Serv. Gen. Tech. Rep. INT-122, 22p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401) at **http://www.fs.fed.us/rm/pubs_int/int_gtr122.pdf**

Idealized Cases

- **To perform a WRF simulation including the ignition and growth of a wildland fire**
  - Change to test directory, test/em_fire
  - Configure your user environment and configure WRF in the usual way
  - Compile the test case:
    - `./compile em_fire`
  - Copy these files from one of the two example directories:
    - the usual input files (`namelist.input` and `input_sounding`)
    - the additional namelist, `namelist.fire` .
  - Configure these for your case
    - `namelist.input` contains an additional section `&fire` with fire model parameters and ignition parameters
    - `namelist.fire` – set fuel moisture (`&fuel_scalars`) here. Contains an additional section (`&fuel_categories`) to customize fuel properties (optional)
  - `./ideal.exe`
  - `./wrf.exe`

namelist.input section &domains

Variable names	Value	Description
&domains		Domain definition
sr_x	10	The fire mesh is 10 times finer than the innermost atmospheric mesh in the *x* direction.
sr_y	10	The fire mesh is 10 times finer than the innermost atmospheric mesh in the *y* direction.

namelist.input section &fire

Variable names	Value	Description
&fire		Fire ignition and fuel parameters
ifire	0	No fires will be simulated.
	2	Fires will be simulated, using the level set method to represent the movement of the interface.
fire_fuel_read	0	How to set the fuel data -1: real data from WPS
		0: set to a homogeneous distribution of fire_fuel_cat everywhere
		1: The spatial distribution of fuel categories is to be specified as a function of terrain altitude. (The user specifies a custom function.)
fire_wind_height	2.	Height to which horizontal wind components are interpolated for fire spread calculations. (Default: 6.096 m, more appropriate is fuel depth - 0.1 - 2. m)

namelist.input section &fire

Variable names	Value	Description
fire_num_ignitions	3	Number of ignition lines, max. 5 allowed
fire_ignition_start_x1	1000.	*x* coordinate of the start point of the ignition line 1. All ignition coordinates are given in m from the lower left corner of the innermost domain
fire_ignition_start_y1	500.	*x* coordinate of the start point of ignition line 1
fire_ignition_end_x1	1000.	*y* coordinate of the end point of ignition line 1. Point ignition (actually a small circle) is obtained by specifying the end point = the start point.
fire_ignition_end_y1	1900.	*y* coordinate of the end point of ignition line 1
fire_ignition_radius1	18.	Everything within fire_ignition_radius1 (in m) from the ignition location will be ignited.
fire_ignition_start_time1	600.	Time of ignition (in s) since the start of the run.
fire_ignition_end_time1	600.	Time ignition ends (in s) since the start of the run.
fire_ignition_ros1	0.01	Rate of spread during ignition. (Default 0.01 m s^{-1}.)
fire_print_msg	1	0: no messages from the fire module 1: progress messages from the fire module

namelist.fire

Variable names	Description
&fuel_scalars	Scalar fuel constants
cmbcnst	The energy released per unit fuel burned for cellulosic fuels (constant, 1.7433×10^{7} J kg^{-1}).
fuelmc_g	Surface fuel, fuel moisture content (in percent, expressed in decimal form, from 0.00 – 1.00).
nfuelcats	Number of fuel categories defined (default: 13)
no_fuel_cat	The number of the dummy fuel category specified to be used where there is 'no fuel'

namelist.fire

Variable names	Description
`&fuel_categories`	Properties of the `nfuelcats` fuel categories
`fgi`	The initial mass loading of surface fuel (in kg m^{-2}) in each fuel category
`fueldepthm`	Fuel depth (m)
`savr`	Fuel surface-area-to-volume-ratio (m^{-1})
`fuelmce`	Fuel moisture content of extinction (in percent expressed in decimal form, from 0.00 – 1.00).
`st`	Fuel particle total mineral content. (kg minerals/kg wood)
`se`	Fuel particle effective mineral content. (kg minerals – kg silica)/ kg wood
`weight`	Time constant (in s) that determines the slope of the mass loss curve. This can range from about 5. (fast burn up) to 1000. (40% decrease in mass over 10 minutes).

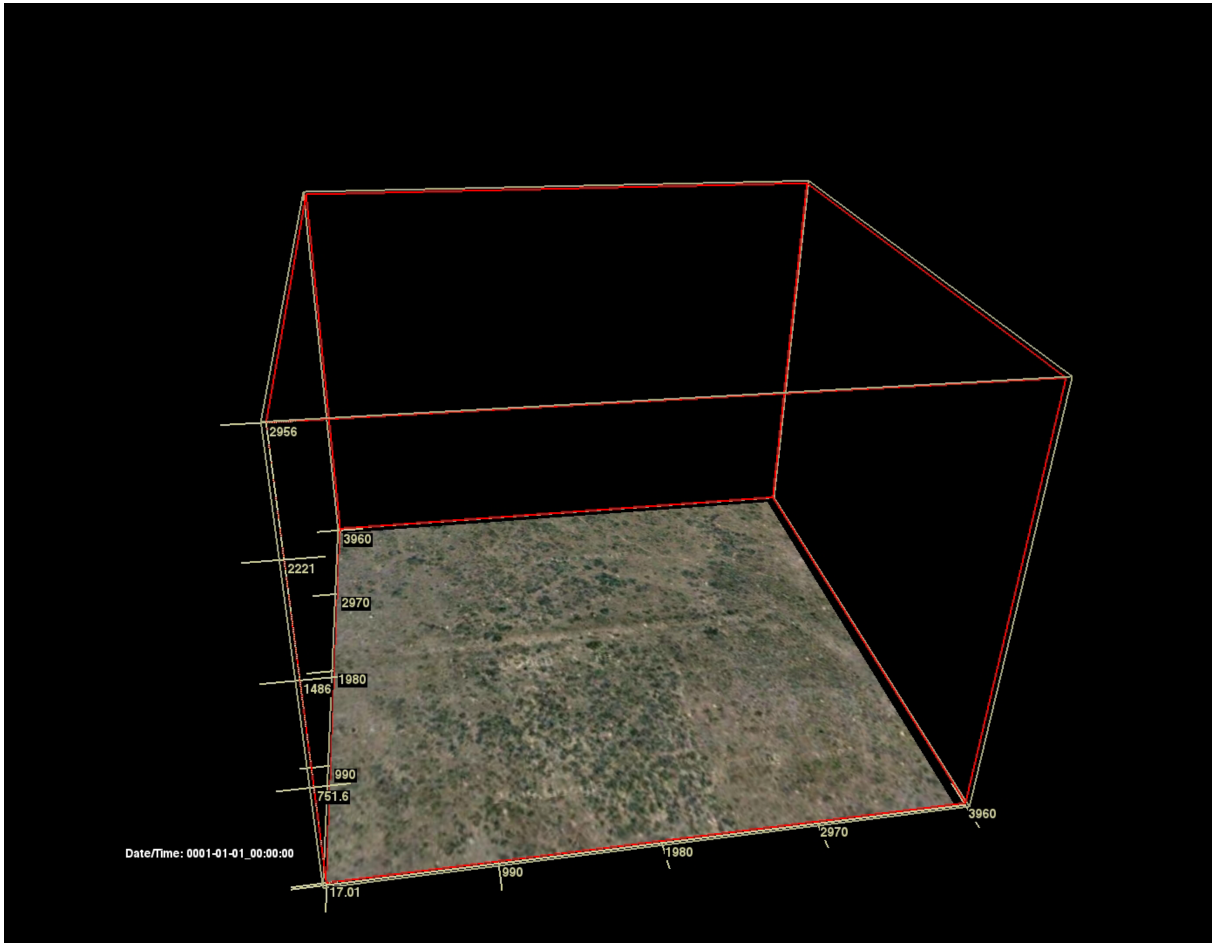
Additional Variables in wrfout* for Analysis

These variables are located at the center of the fire grid cells.

LFN	level set function. Node (i,j) is on fire if LFN(i,j)<=0
FXLONG, FXLAT	longitude and latitude of the nodes
FGRNHFX	heat flux from the surface fire (W m^{-2}), averaged over the cell
FGRNQFX	heat flux from the surface fire (W m^{-2}), averaged over the cell
ZSF	terrain elevation above sea level (m)
UF,VF	surface wind
FIRE_AREA	fractional part of the area of the fuel cell that is on fire, between 0 and 1

Example

Fire spreading in tall grass (Fuel model 3)



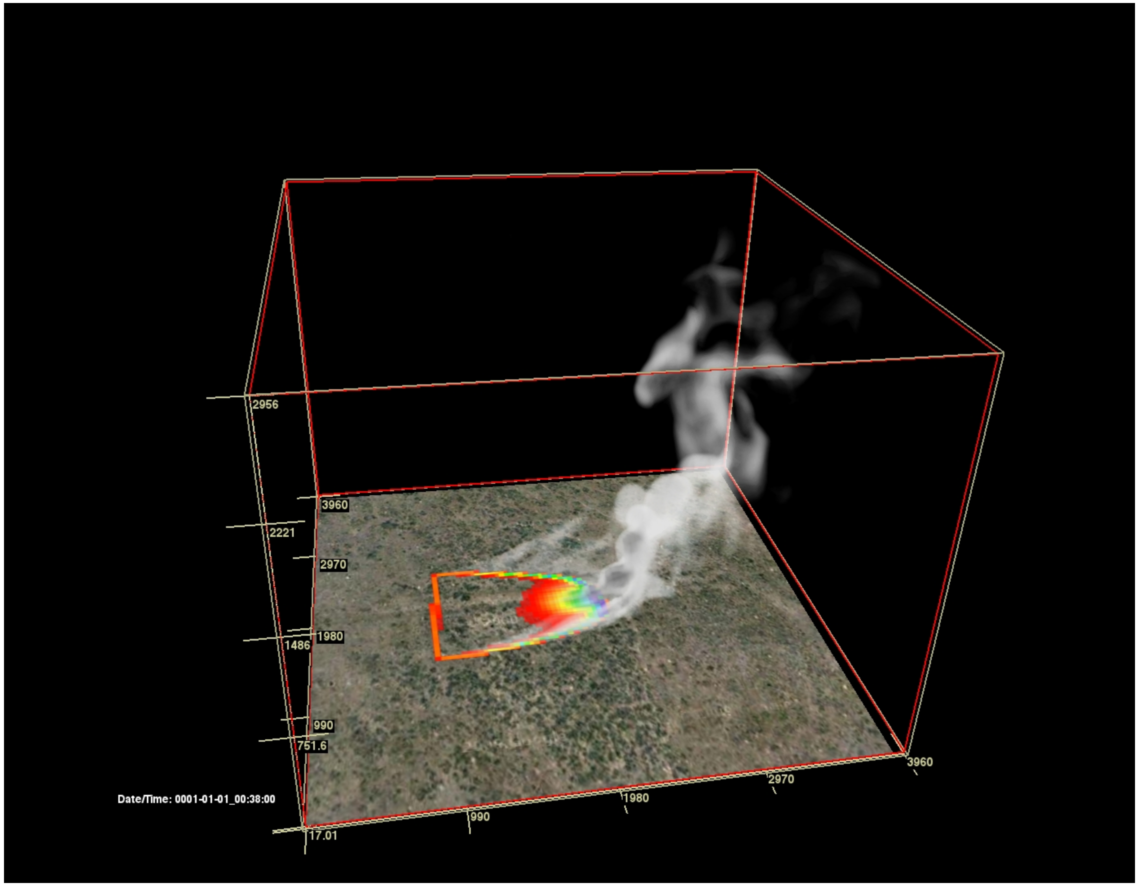
Color contours: `FGRNHFX`, the fire's sensible heat flux

Misty field: volume rendering of water vapor mixing ratio

Visualization with VAPOR, http://www.vapor.ucar.edu

Example

Fire spreading in tall grass (Fuel model 3)



Color contours: `FGRNHFX`, the fire's sensible heat flux

Misty field: volume rendering of water vapor mixing ratio

Visualization with VAPOR, http://www.vapor.ucar.edu

Real Case

To perform a WRF simulation in a ‘real’ case: user provides additional data.

- **Configure your user environment and configure WRF in usual way before WPS**
- **Compile the real case:**
  - `./compile em_real`
- **WPS**
  - Configure and compile WPS from the ./WPS directory:
    - `./configure`
    - `./compile`
  - Ungrib and metgrid are used the same way. Additional datasets and variables are needed for geogrid (See session “WPS Advanced Usage”):
    - `NFUEL_CAT` - Spatial map of fuel categories. *User supplies data*.
      - See Landfire (http://landfire.cr.usgs.gov/viewer/)
    - `ZSF` – high resolution terrain (less than 30 arc sec). *User supplies data*.
    - `Add NFUEL_CAT and ZSF to` in `GEOGRID.TBL`

Real Case

- Configure namelist.wps with an additional parameter:

Variable	Description
subgrid_ratio_[xy]	The refinement ratio from the atmospheric grid to the fire grid.

- Run WPS components (./geogrid.exe, ./ungrib.exe, ./metgrid.exe)

- **WRF**
  - As in ideal experiment, include the extra fire variables in `namelist.input` and `namelist.fire`
  - `./real.exe`
  - `./wrf.exe`

Configuration

- Success depends on capturing (1) near surface winds at the scale you are modeling and (2) the effect the fire's heat fluxes have on the atmosphere

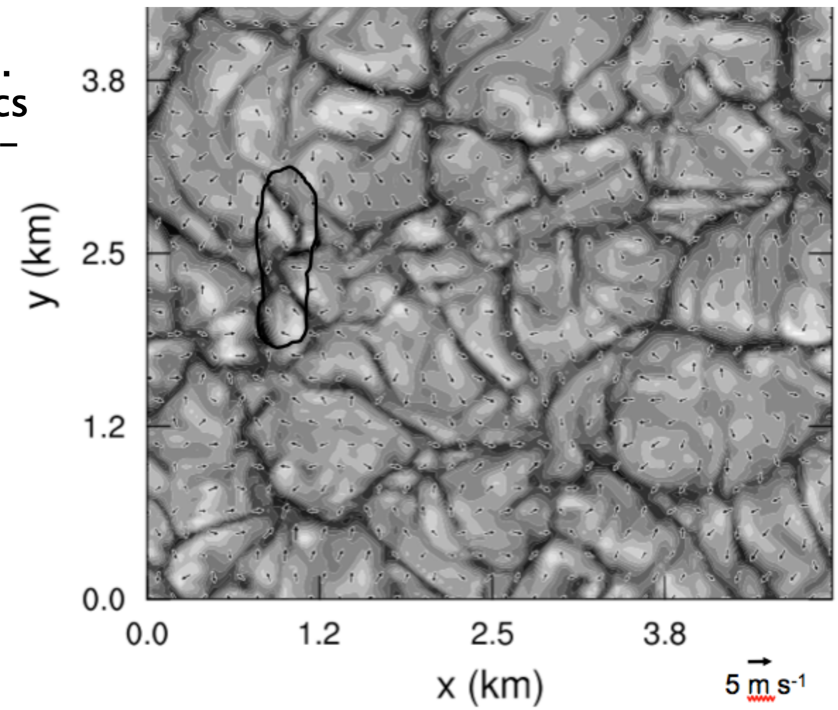
- Confirm your grid spacings in `namelist.input` make sense, considering that:
  - Fire lines are only ~10–100 m wide
  - Heat is released into the bottom of the atmosphere over a 10–50 m vertical depth

- Best practices:

(a) 1-domain, ideal experiment, with dx & dy < 100 m. Run in large eddy simulation (LES) mode (bl_pbl_physics =0) with surface stress or heating. Periodic BCs. Cubic-ish grids. Allow boundary layer eddies to build over several hours (Coen et al. 2013)

(b) Real experiment with multiple nested domains refining to dx & dy ~1km. Fire occurs in innermost domain.

Do not refine to < 100 m ("LES scale") with multiple domains just because you have computing resources to do so. Motions at this scale are dominated by boundary layer eddies and require the techniques in example (a) to develop the right energy spectrum.



Caveats

- **This represents a fire spreading on the surface**
  - In a forest, this model represents the creeping spread of fire on the ground below the branches, not crown fires that spread through the canopy (and require other algorithms)
- **Success of simulation depends on capturing near-surface winds and the feedbacks on the atmosphere**
- **Data for real experiment**
  - Confirm geospatial data source is projected to WGS84
  - If creating your own fuel properties from landcover data, note that fuel load is what burns, not the whole vegetation biomass (like trunks)