

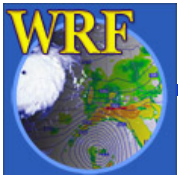


# WRF-Fire: A physics package for modeling wildland fires

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*NCAR*

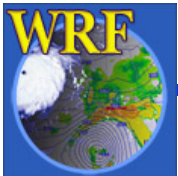
*Mesoscale and Microscale Meteorology Division*



# Introduction

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- **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

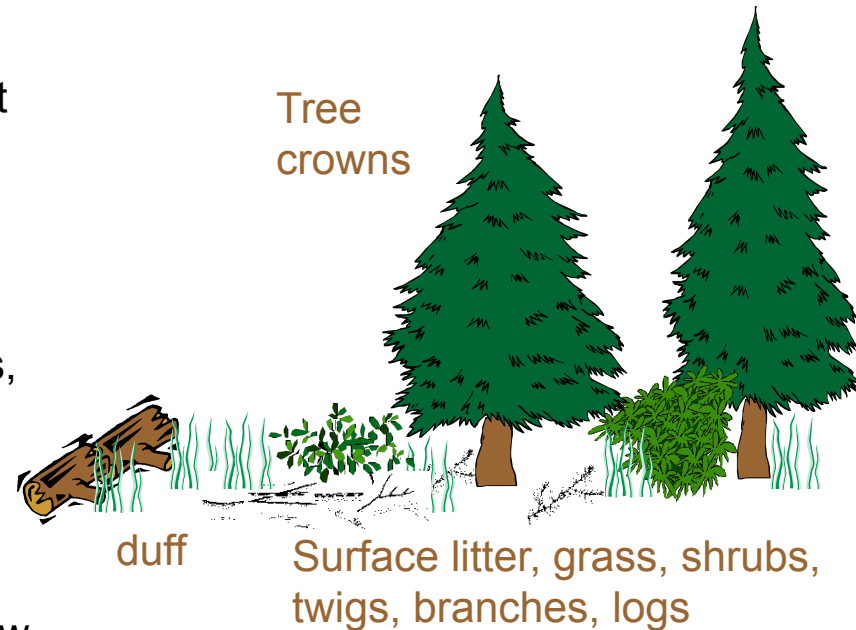
## Weather

wind, temperature, relative humidity, precipitation

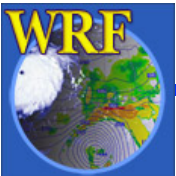
**Weather CHANGES:** fronts, downslope winds, storm downdrafts, sea/land breezes, diurnal slope winds

## Topography

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

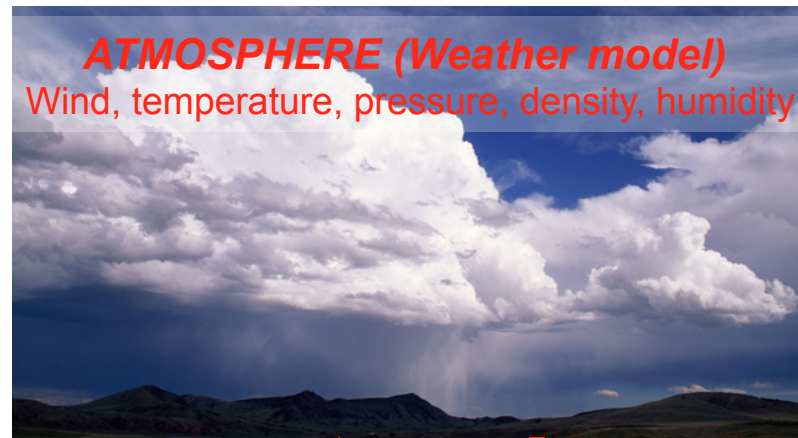


*These are not independent*



# Coupled Weather – Wildland Fire Modeling

## FIRE-WEATHER FEEDBACKS

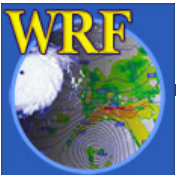


The atmosphere (i.e. wind) exerts a force on fires, directing where/how fast they spread and affects fuel properties like fuel moisture that determine whether/how intensely a fire will burn.

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

Convective fingers

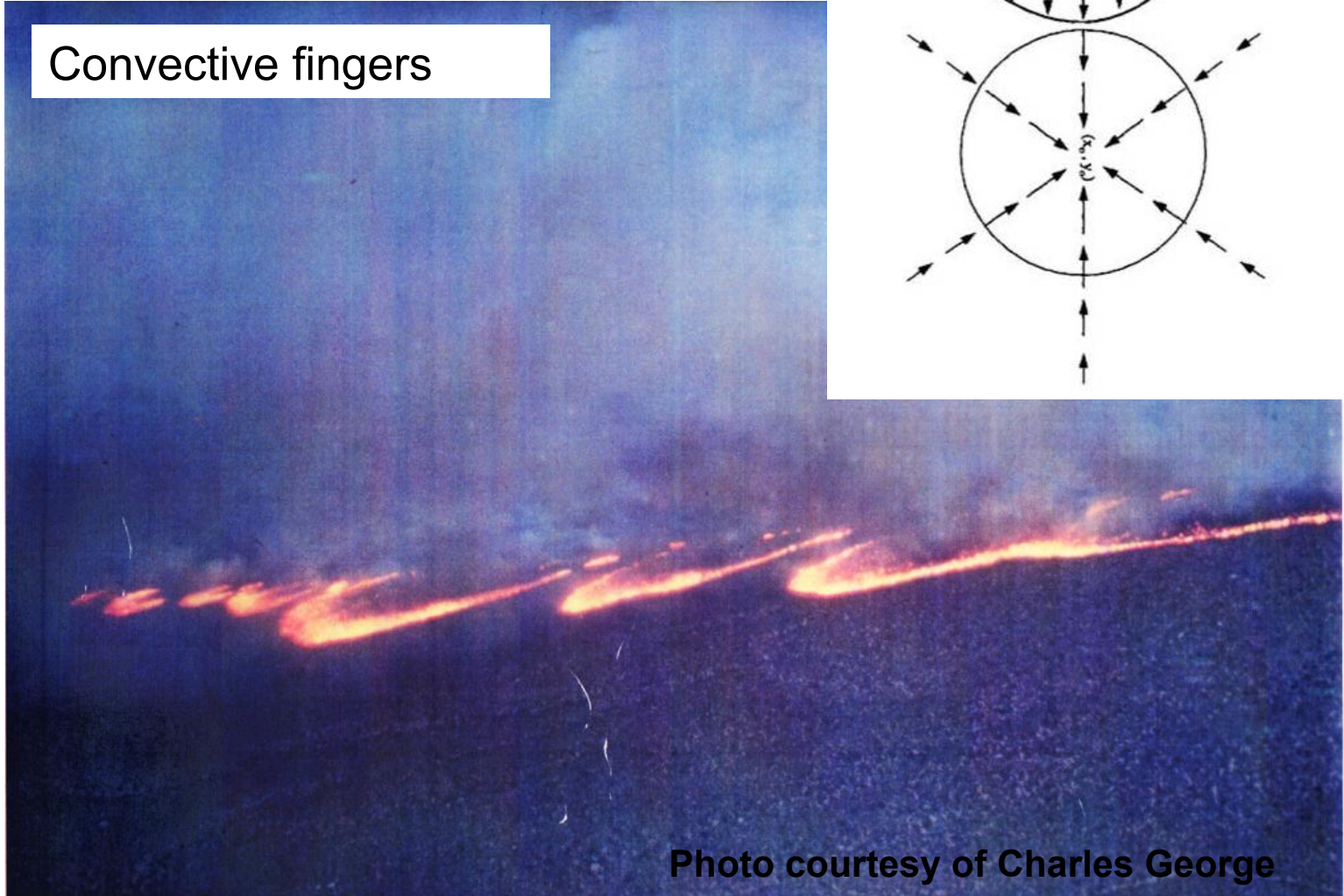
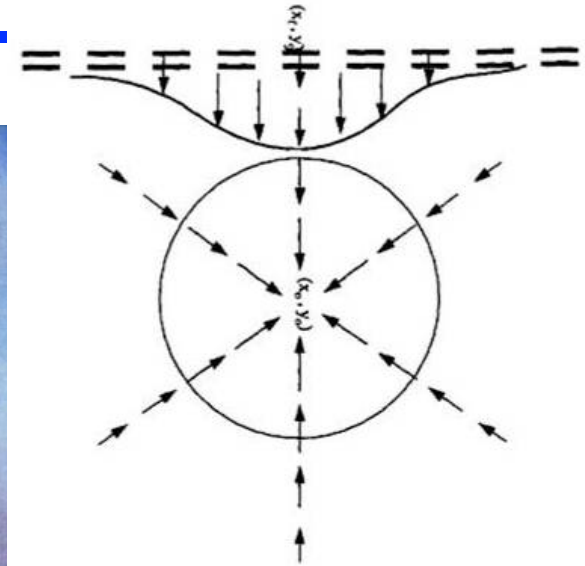
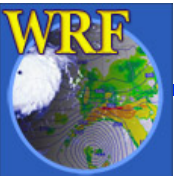


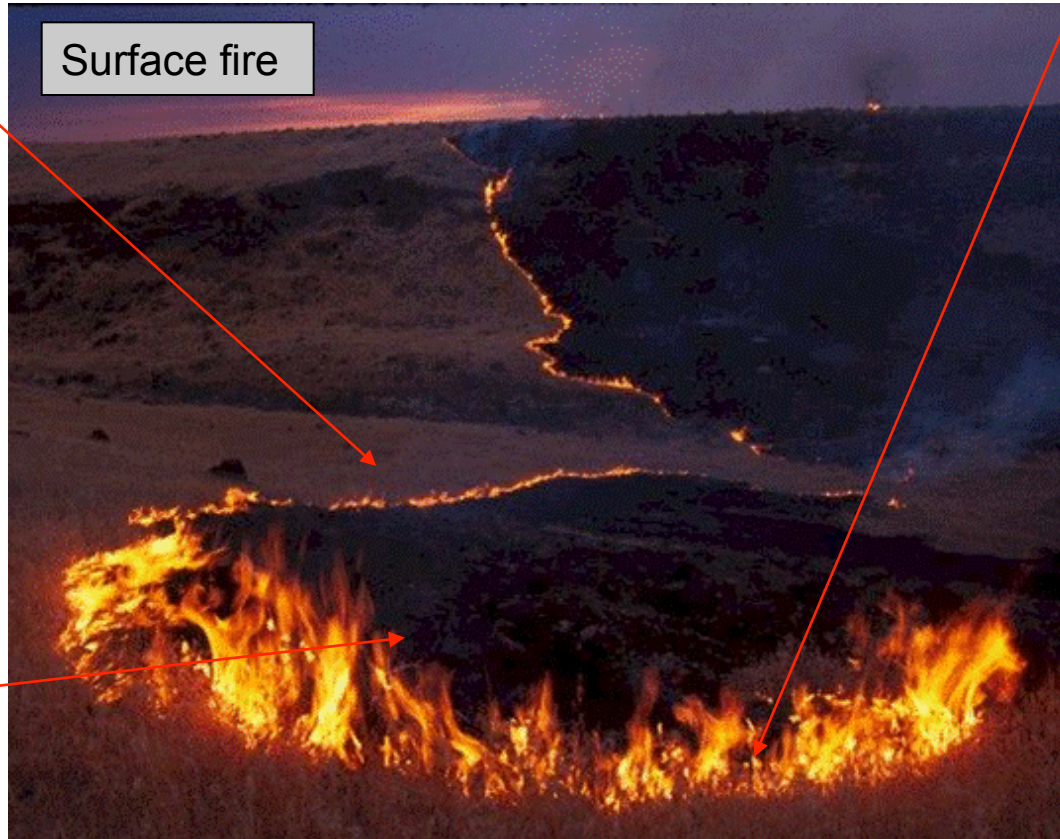
Photo courtesy of Charles George



# Physical Processes

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

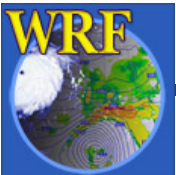
Surface fire



Post-frontal  
heat & water  
vapor release

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

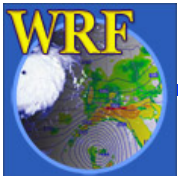
Heat, water vapor,  
and smoke fluxes  
released by  
simulated fire into  
lowest layers of  
atmospheric model



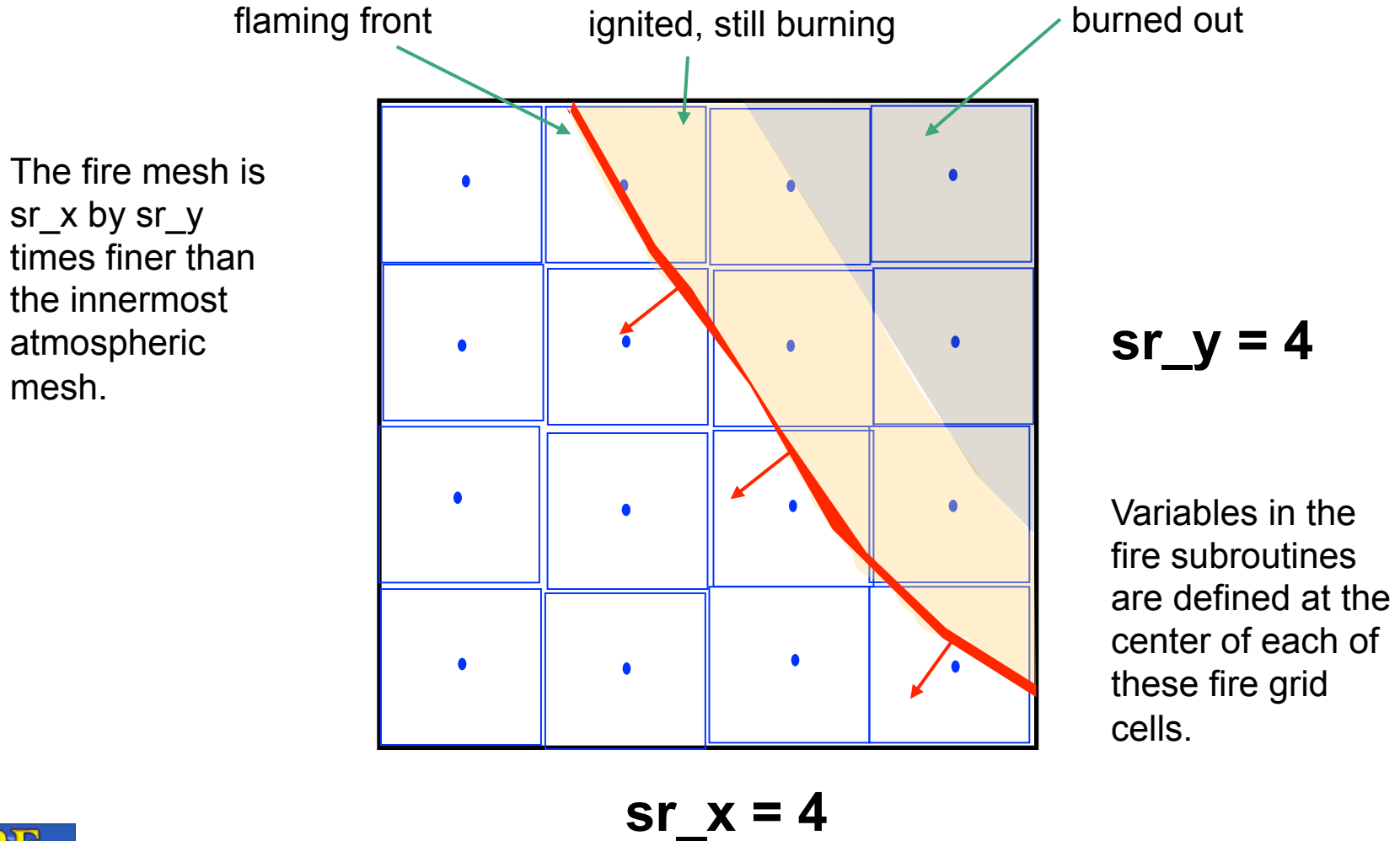
# What do these subroutines do?

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- **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<sup>2</sup>), or W/m<sup>2</sup>).
  - Sum up the heat release for all the fire cells within each atmospheric cells.
    - Sensible heat flux (temperature) – W m<sup>-2</sup>
    - Latent heat flux (water vapor) - W m<sup>-2</sup>
      - 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



# Spread Rate of a Flaming Front

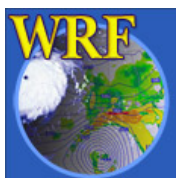
(Semi-empirical) Rothmel eqns (1972)

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

Zero-wind spread rate on flat ground
wind factor
slope factor

Heat energy of fuel  
 Heat required to prepare fuel & ignite

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



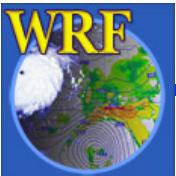
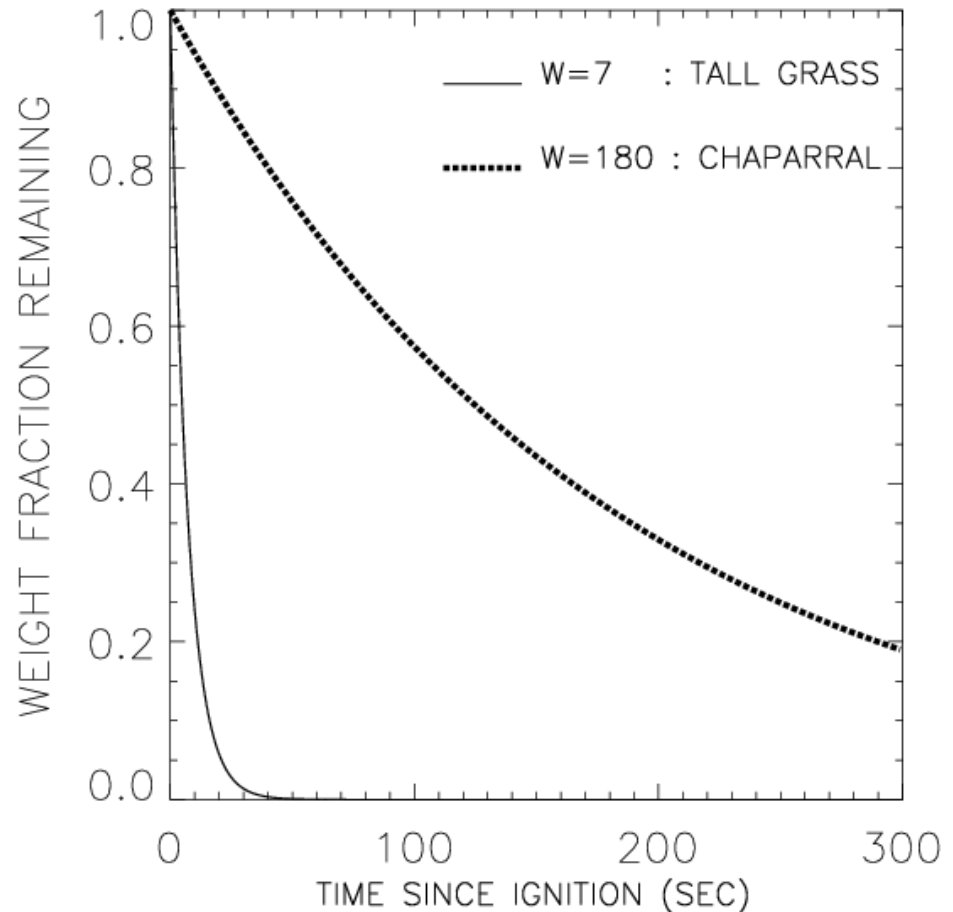
# Mass loss rate after ignition

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.

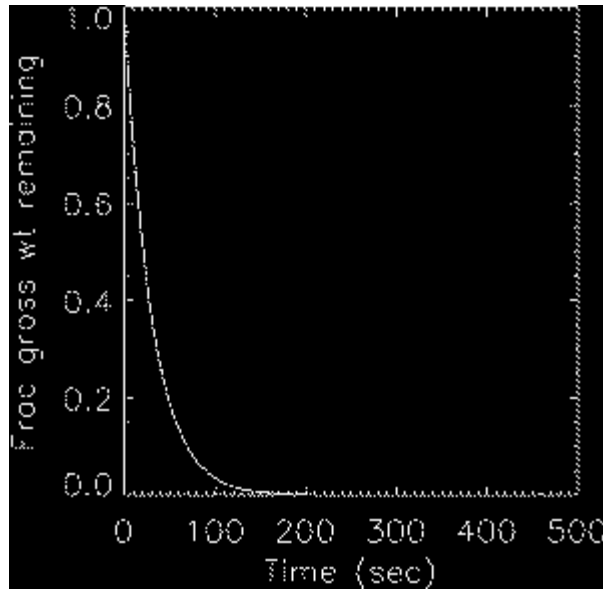


## Fraction of fuel remaining with time

**“Flashy”  
fuels**

Grass

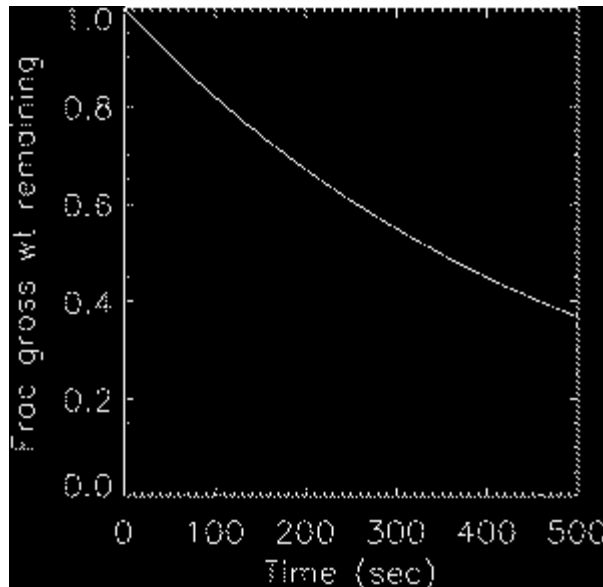
W=30 s



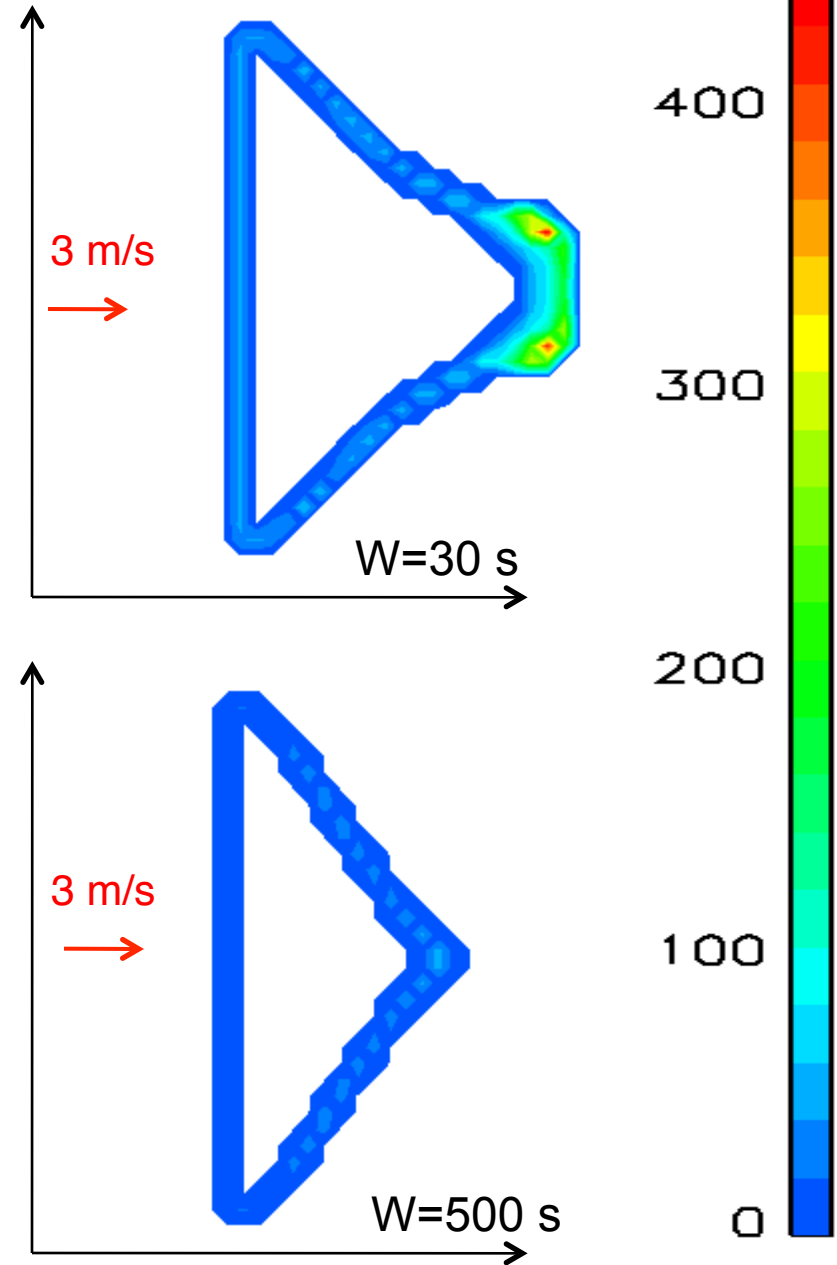
**Slow-  
burning**

Woody fuel  
mixture

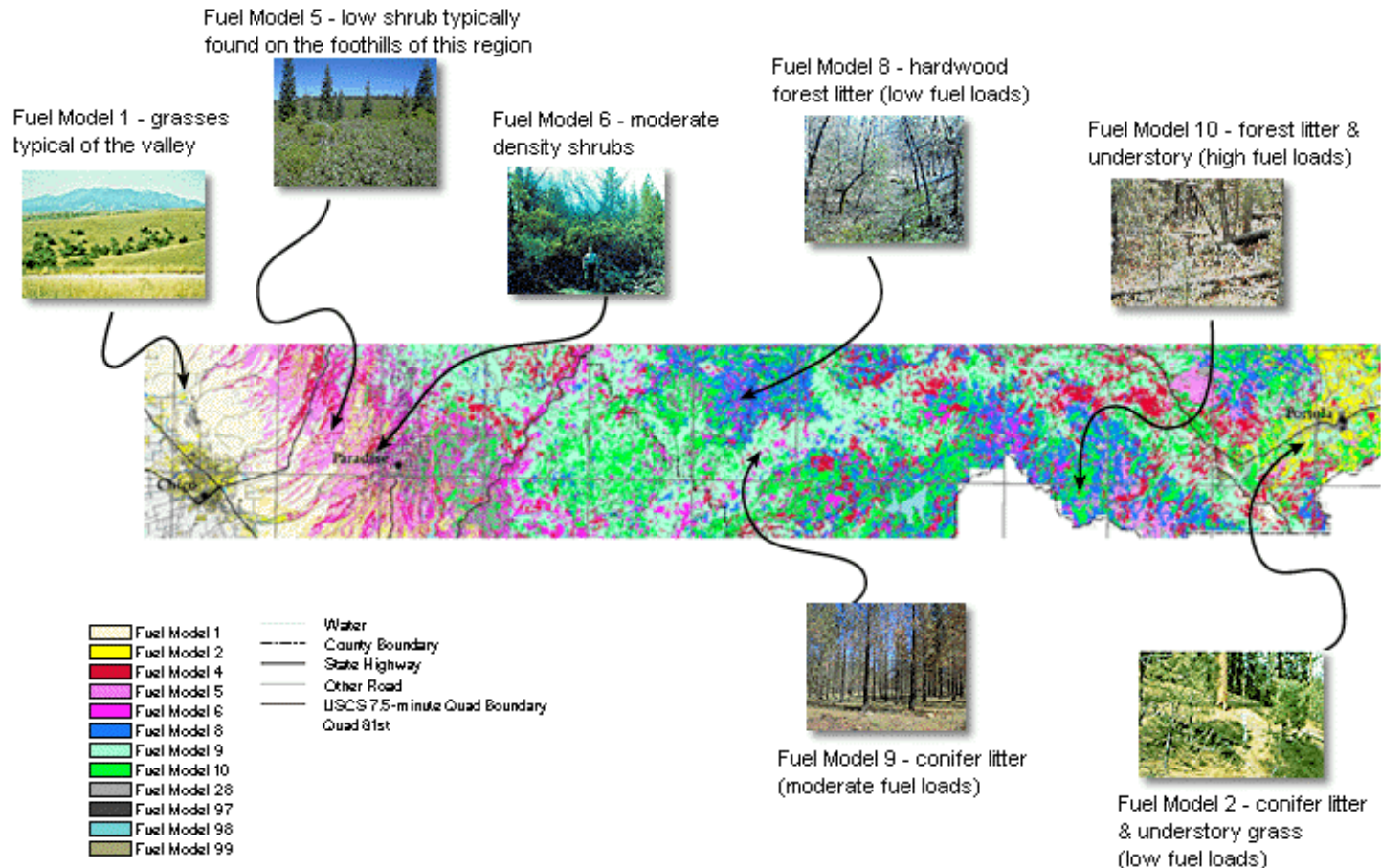
W=500 s



## Heat flux(kW/m<sup>2</sup>)

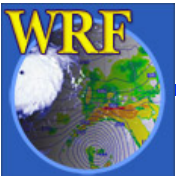


A “Fuel Model” is a collection of fuel properties based on the amount, physical properties, and spatial distribution of surface fuel elements



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        |          |           |      | Fuel bed depth | Moisture of extinction<br>dead fuels |
|------------|-----------------------------------|---------------------|----------|-----------|------|----------------|--------------------------------------|
|            |                                   | 1 hour              | 10 hours | 100 hours | Live |                |                                      |
|            |                                   | -----Tons/acre----- |          |           |      | Feet           | Percent                              |
|            | <b>Grass and grass-dominated</b>  |                     |          |           |      |                |                                      |
| 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                                   |
|            | <b>Chaparral and shrub fields</b> |                     |          |           |      |                |                                      |
| 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                                   |
|            | <b>Timber litter</b>              |                     |          |           |      |                |                                      |
| 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                                   |
|            | <b>Slash</b>                      |                     |          |           |      |                |                                      |
| 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                                   |

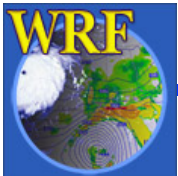
Anderson, H. E. 1982. *Aids to determining fuel models for estimating fire behavior*. USDA For. Serv. Gen. Tech. Rep. INT-122, 22p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401) at [http://www.fs.fed.us/rm/pubs\\_int/int\\_gtr122.pdf](http://www.fs.fed.us/rm/pubs_int/int_gtr122.pdf)



# Idealized Cases

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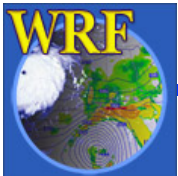
- To perform a WRF simulation including the ignition and growth of a wildland fire
  - Change to test directory, `test/em_fire`
  - Configure your user environment and configure WRF in the usual way
  - Compile the test case:
    - `./compile em_fire`
  - Copy these files from one of the two example 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

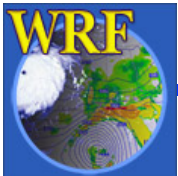
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| Variable names | Value | Description                                                                             |
|----------------|-------|-----------------------------------------------------------------------------------------|
| &domains       |       | 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. |



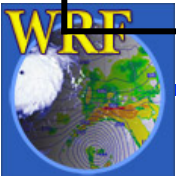
# namelist.input section &fire

| 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<br>-1: real data from WPS                                                                                                        |
|                  |       | 0: set to a homogeneous distribution of<br>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) |



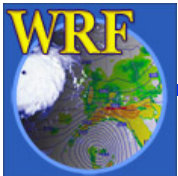
# namelist.input section & fire

| 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 <sup>-1</sup> .)                                                                                    |
| fire_print_msg            | 1     | 0: no messages from the fire module<br>1: progress messages from the fire module                                                                      |



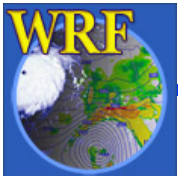
# namelist.fire

| Variable names | Description                                                                                                        |
|----------------|--------------------------------------------------------------------------------------------------------------------|
| &fuel_scalars  | Scalar fuel constants                                                                                              |
| cmbcnst        | The energy released per unit fuel burned for cellulosic fuels (constant, $1.7433 \times 10^7 \text{ J kg}^{-1}$ ). |
| 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

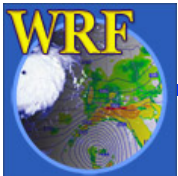
| Variable names   | Description                                                                                                                                                          |
|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| &fuel_categories | Properties of the <code>nfuelcats</code> fuel categories                                                                                                             |
| fgi              | The initial mass loading of surface fuel (in $\text{kg m}^{-2}$ ) in each fuel category                                                                              |
| fueldepthm       | Fuel depth (m)                                                                                                                                                       |
| savr             | Fuel surface-area-to-volume-ratio ( $\text{m}^{-1}$ )                                                                                                                |
| 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

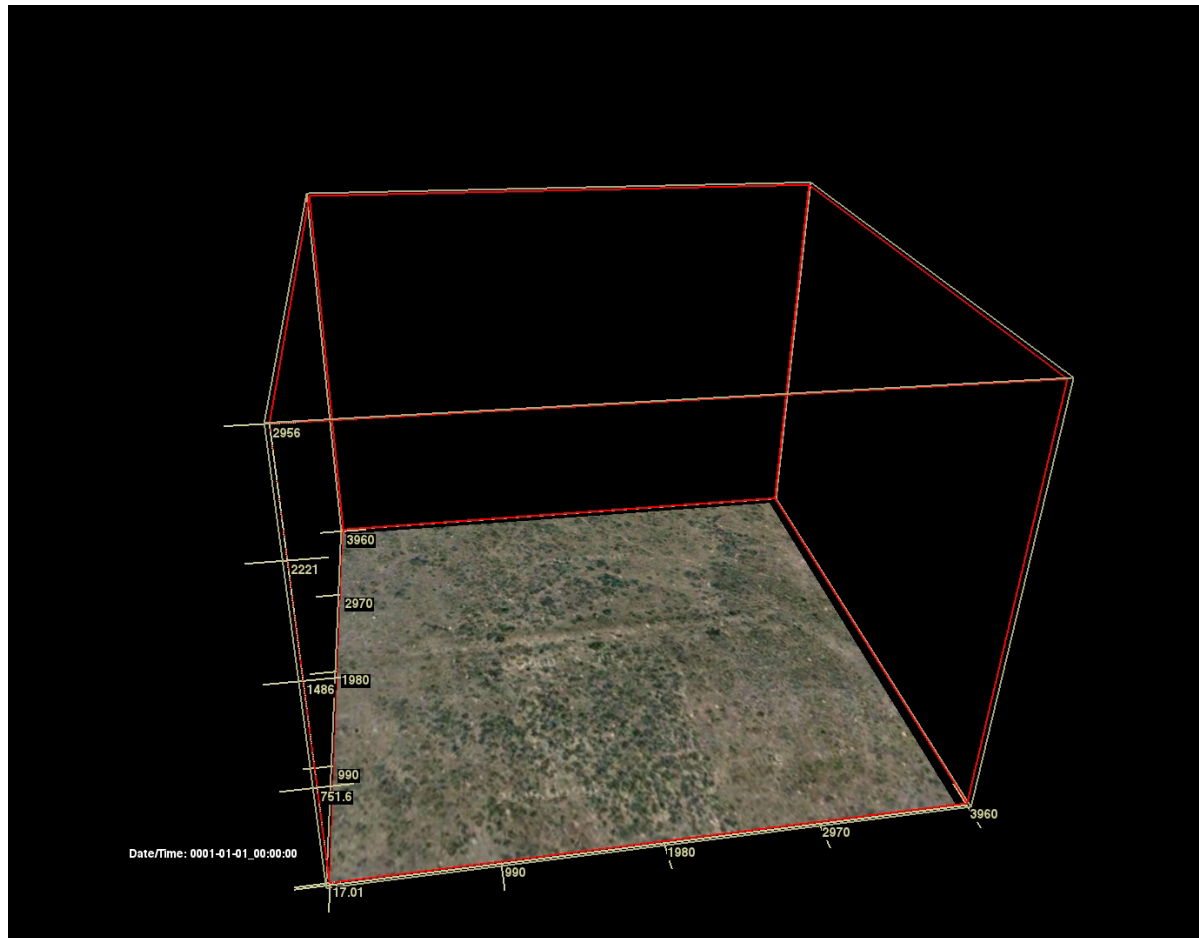
These variables are located at the center of the fire grid cells.

|               |                                                                               |
|---------------|-------------------------------------------------------------------------------|
| LFN           | level set function. Node (i,j) is on fire if $\text{LFN}(i,j) \leq 0$         |
| FXLONG, FXLAT | longitude and latitude of the nodes                                           |
| FGRNHFX       | heat flux from the surface fire ( $\text{W m}^{-2}$ ), averaged over the cell |
| FGRNQFX       | heat flux from the surface fire ( $\text{W m}^{-2}$ ), 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

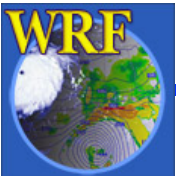
## Fire spreading in tall grass (Fuel model 3)



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

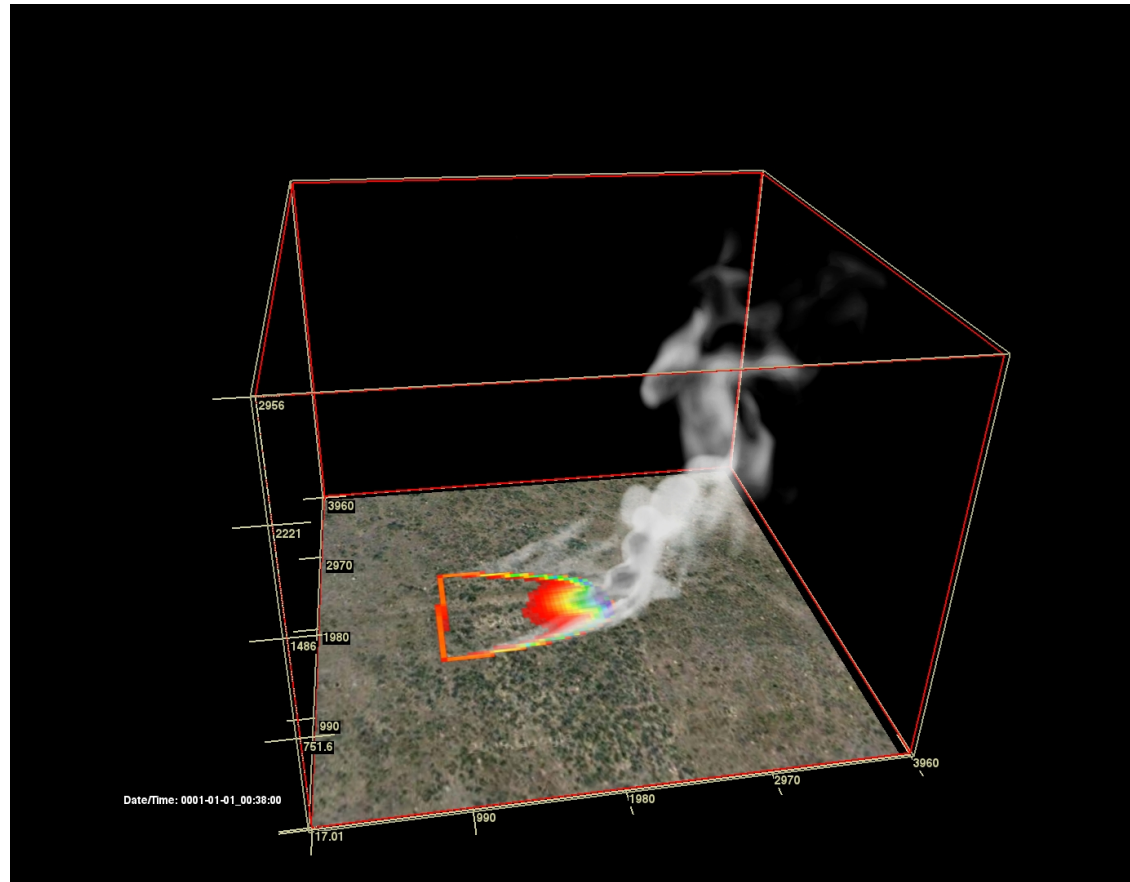
**Misty field:**  
volume  
rendering of  
water vapor  
mixing ratio

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



# Example

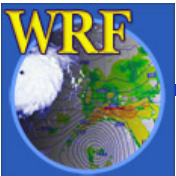
## Fire spreading in tall grass (Fuel model 3)



**Color contours:**  
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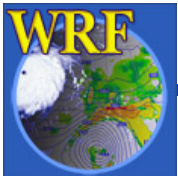
Visualization with VAPOR, <http://www.vapor.ucar.edu>



# 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

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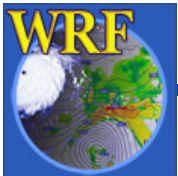
- Configure namelist.wps with an additional parameter:

| Variable                        | Description                                                      |
|---------------------------------|------------------------------------------------------------------|
| <code>subgrid_ratio_[xy]</code> | 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

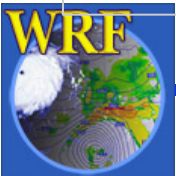
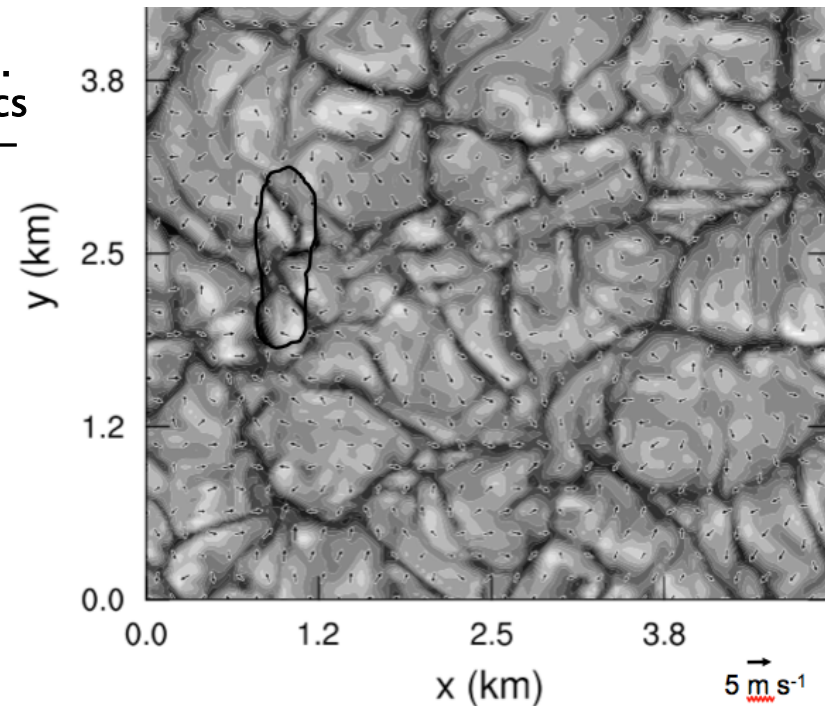
- Success depends on capturing (1) near surface winds at the scale you are modeling and (2) the effect the fire's heat fluxes have on the atmosphere
- Confirm your grid spacings in `namelist.input` make sense, considering that:
  - Fire lines are only ~10–100 m wide
  - Heat is released into the bottom 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  **$dx$  &  $dy \sim 1$  km**. 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 fuelload is what burns, not the whole vegetation biomass (like trunks)

