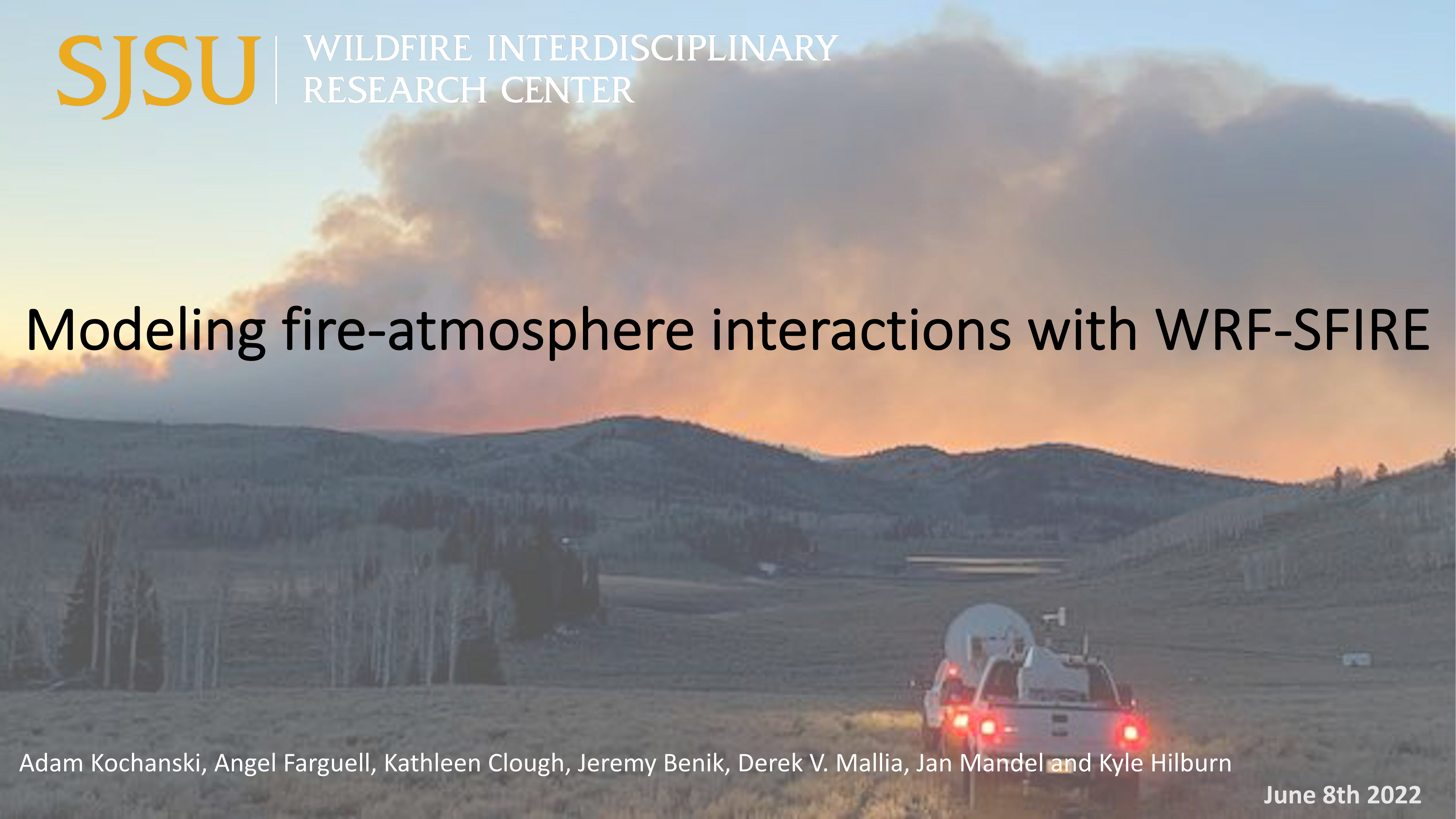


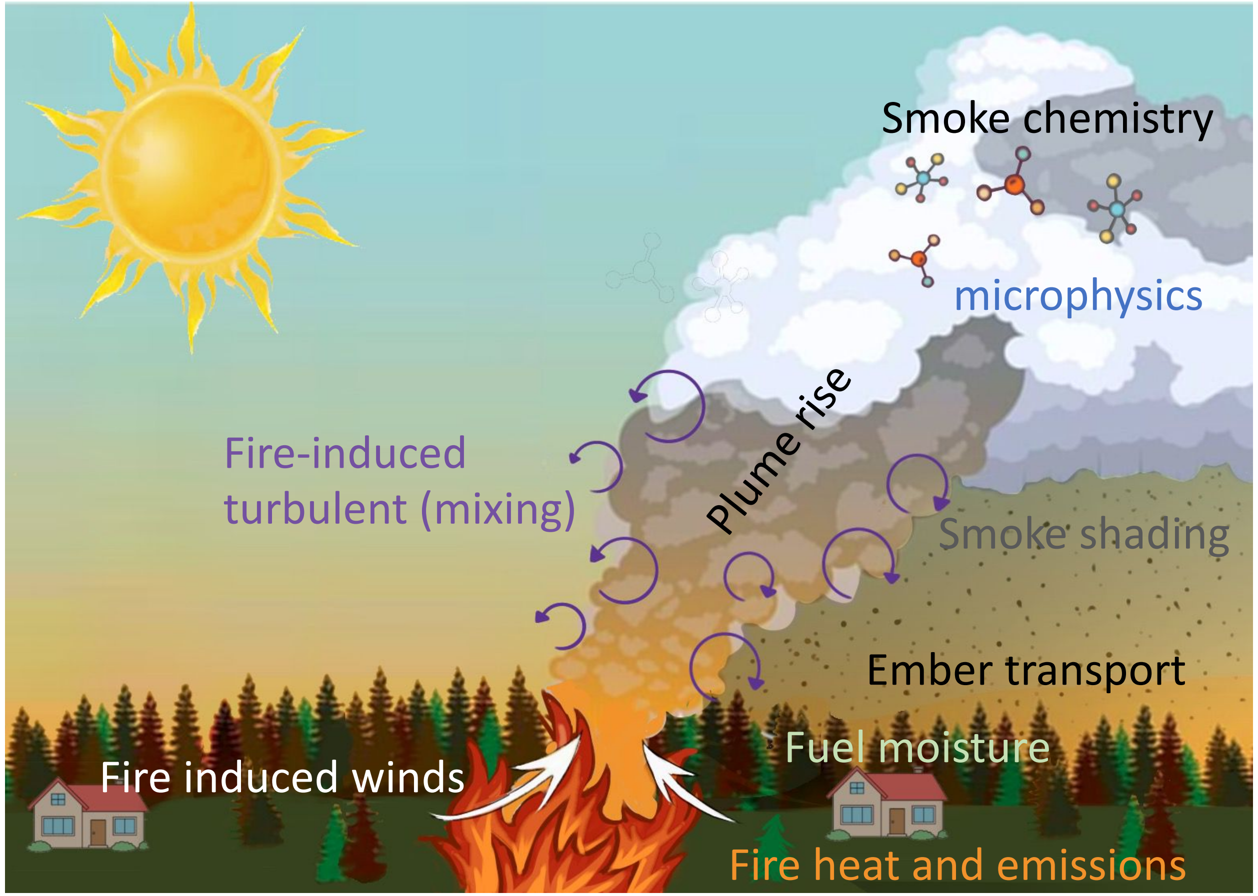
SJSU | WILDFIRE INTERDISCIPLINARY RESEARCH CENTER

Modeling fire-atmosphere interactions with WRF-SFIRE

Adam Kochanski, Angel Farguell, Kathleen Clough, Jeremy Benik, Derek V. Mallia, Jan Mandel and Kyle Hilburn

June 8th 2022

Fire-atmosphere interactions



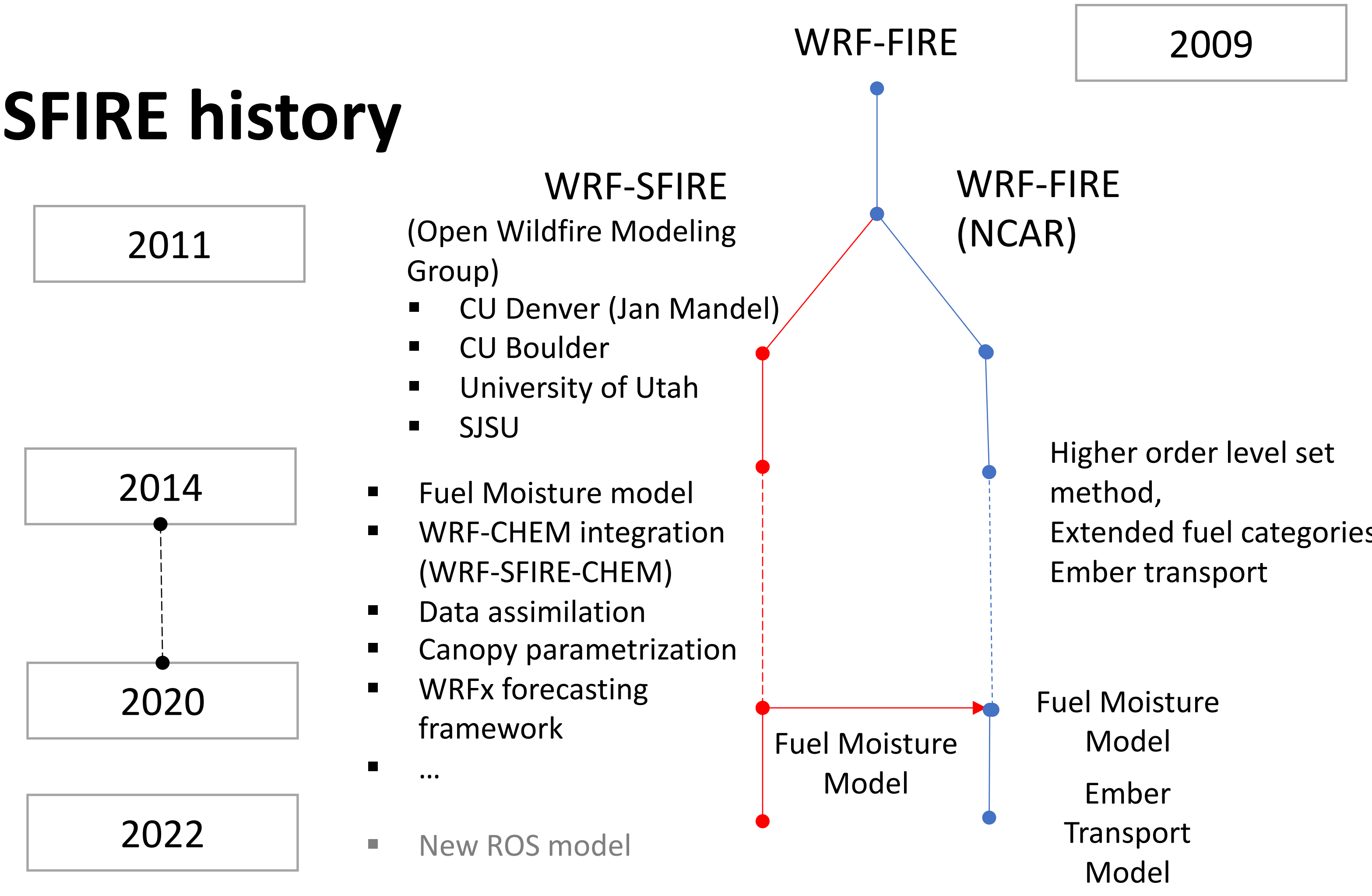
Convective updrafts create fire-winds. Changes in local meteorology impact fuel moisture and fire activity.
Smoke can alter local meteorological conditions by inducing surface cooling, weakening winds, and reducing fuel dryness

- Inflow into the convective column generates local winds interacting with the fire dynamics
- Buoyant plume induces turbulent mixing and vertical momentum transfer which can modify surface wind conditions
- Fire behavior and plume dynamics are linked not only to the weather conditions but also to the fuel moisture
- Smoke particles absorb incoming solar radiation, affecting the surface energy balance and reducing surface temperatures (smoke shading)
- The reduced surface heating limits convective mixing and inhibits evolution of the planetary boundary layer
- As a consequence, local meteorological conditions in regions affected by smoke can differ substantially from the conditions in regions not affected by smoke
- Aerosols and gaseous species impact microphysics, smoke composition and air quality
- All above processes feed back to local meteorology impacting fire and plume dynamics

WRF-SFIRE history

- WRF-SFIRE originally developed under the name WRF-Fire (Mandel et al. 2009, 2011), couples a 2D fire spread model using a level set method with the fire Rate of Spread (ROS) from the Rothermel (1972) formula, with the WRF atmospheric model (Skamarock et al. 2008).
- WRF-Fire/WRF- SFIRE originated from the coupled model by Clark et al. (1996, 2004), later CAWFE (Coen 2013), by replacing fire tracers by the level set method and the Clark-Hall atmospheric model (Clark 1977) by WRF.
- Since 2011 WRF-SFIRE and WRF-FIRE diverged, with a periodic transfer of components from WRF-SFIRE to WRF-FIRE
- Both versions are included in the WRF-SFIRE repository available at: git://github.com/openwfm/WRF-SFIRE.git with:

  WRF-SFIRE activated by: ifire= 1,
  WRF-FIRE activated by: ifire = 2,



WRF-SFIRE
(Open Wildfire Modeling Group)

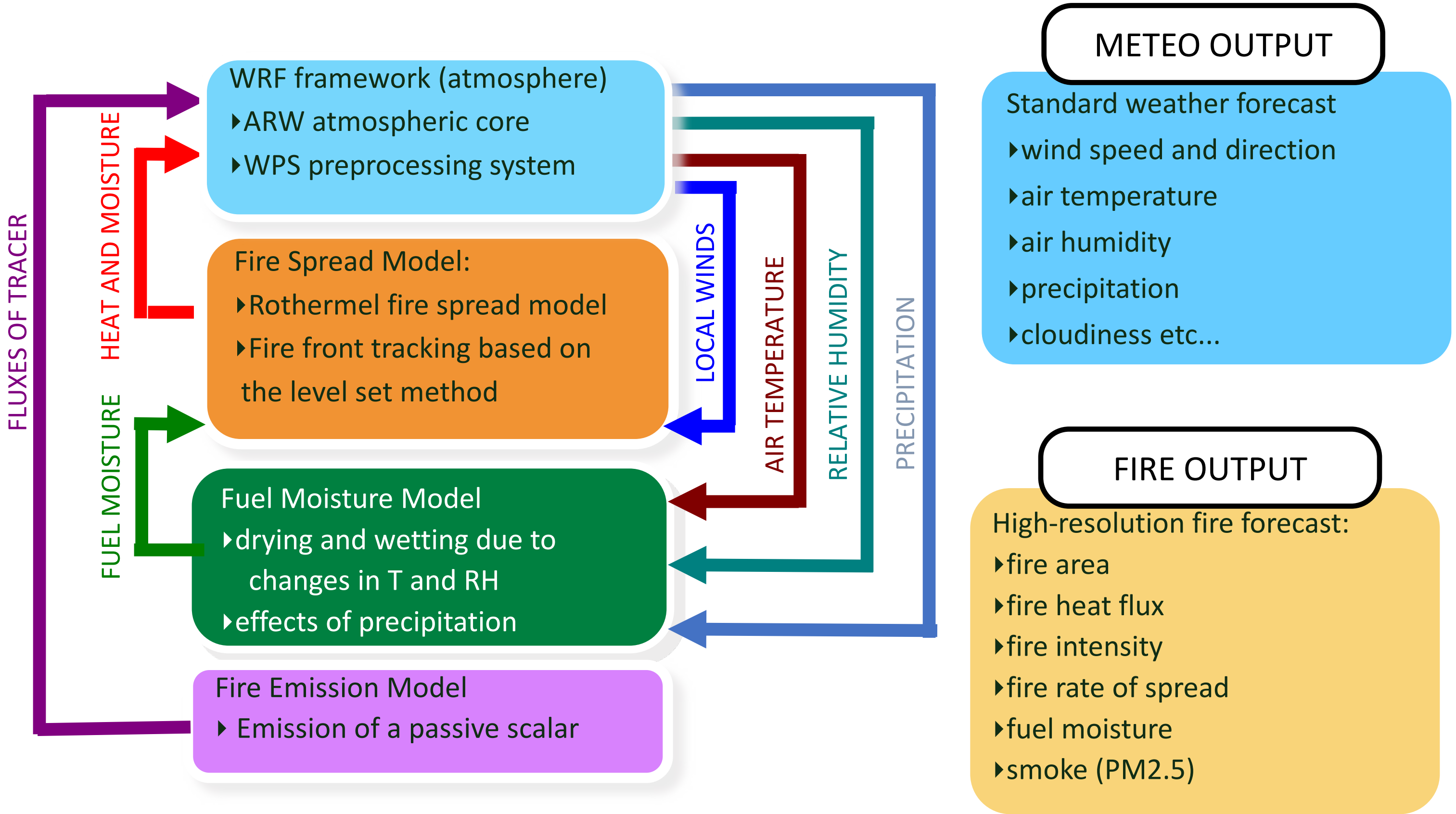
- CU Denver (Jan Mandel)
- CU Boulder
- University of Utah
- SJSU

- Fuel Moisture model
- WRF-CHEM integration (WRF-SFIRE-CHEM)
- Data assimilation
- Canopy parametrization
- WRFx forecasting framework
- …
- New ROS model

Higher order level set method,
Extended fuel categories
Ember transport

Mandel, J., J. D. Beezley, J. L. Coen, and M. Kim, 2009: Data assimilation for wildland fires: Ensemble Kalman filters in coupled atmosphere-surface models. IEEE Control Systems Magazine, 29, 47–65, doi:10.1109/MCS.2009.932224.
Mandel, J., J. D. Beezley, and A. K. Kochanski, 2011: Coupled atmosphere-wildland fire modeling with WRF 3.3 and SFIRE 2011. Geoscientific Model Development, 4, 591– 610, doi:10.5194/gmd-4-591- 2011.
Kochanski A. K., Jenkins M.A., Yedinak K., Mandel J., Beezley J, and Lamb B. (2015) Toward an integrated system for fire, smoke and air quality simulations, International Journal of Wildland Fire - http://dx.doi.org/10.1071/WF14074
Kochanski, A. K., Mallia, D. V., Fearon, M. G., Mandel, J., Souri, A. H., & Brown, T. (2019). Modeling wildfire smoke feedback mechanisms using a coupled fire-atmosphere model with a radiatively active aerosol scheme. Journal of Geophysical Research: Atmospheres, 124. https://doi.org/10.1029/2019JD030558

Data Flow and Components of WRF-SFIRE



WRF framework (atmosphere)
- ARW atmospheric core
- WPS preprocessing system

Fire Spread Model:
- Rothermel fire spread model
- Fire front tracking based on the level set method

Fuel Moisture Model
- drying and wetting due to changes in T and RH
- effects of precipitation

Fire Emission Model
- Emission of a passive scalar

METEO OUTPUT

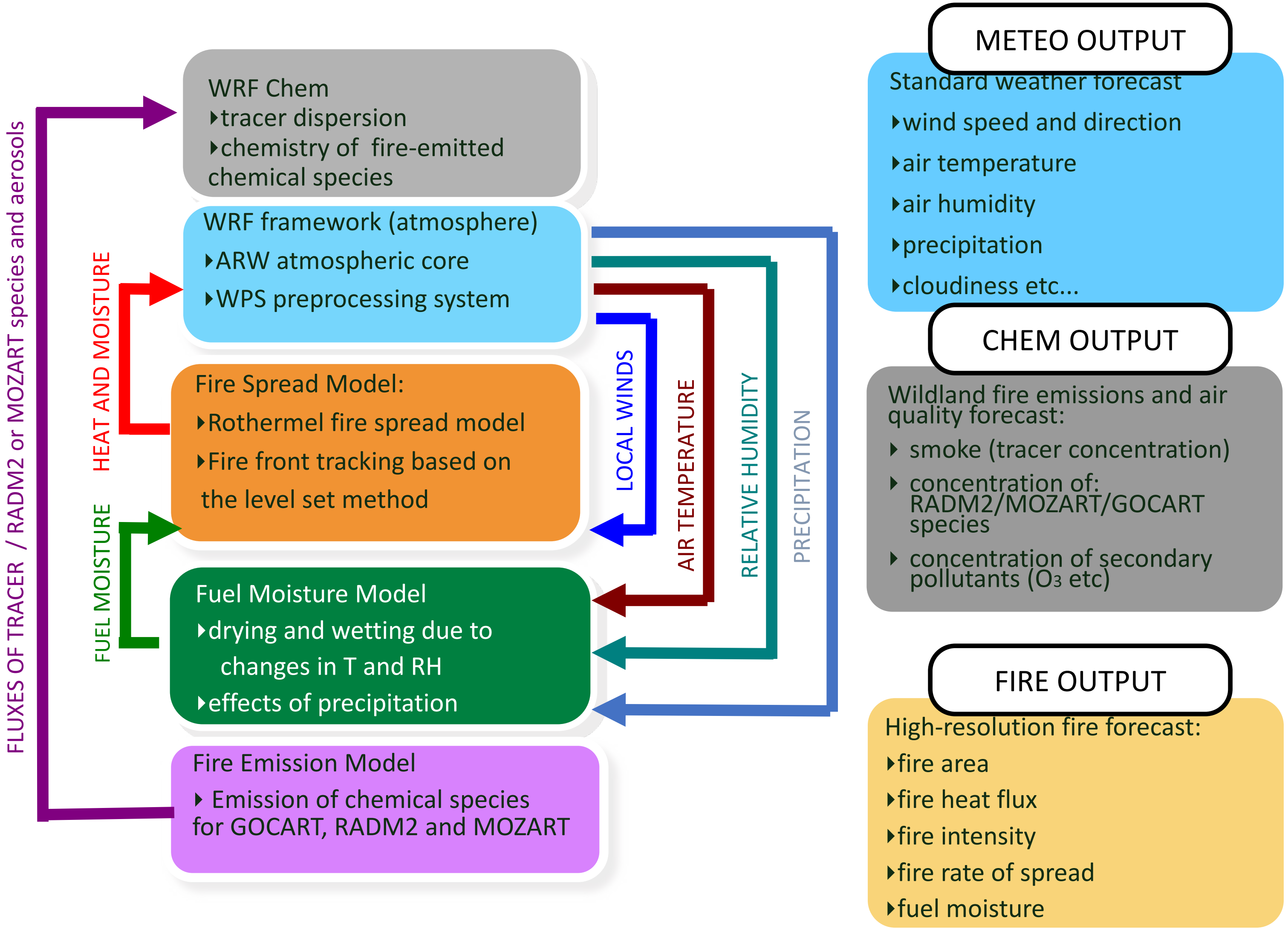
Standard weather forecast
- wind speed and direction
- air temperature
- air humidity
- precipitation
- cloudiness etc...

FIRE OUTPUT

High-resolution fire forecast:
- fire area
- fire heat flux
- fire intensity
- fire rate of spread
- fuel moisture
- smoke (PM2.5)

- Fire progression is simulated in-line with local meteorology
- Heat, moisture and smoke are computed based on the fire characteristics (geometry and intensity)
- Fire propagation is traced on a refined fire mesh typically 30m resolution using high resolution fuel maps and topography
- Plume dynamics and smoke dispersion are resolved on the model grid w/o external parametrizations
- On-line fuel moisture model resolves fluctuation in the fuel moisture due to changing weather conditions

Data flow and components of WRF-SFIRE-CHEM



FLUXES OF TRACER / RADM2 or MOZART species and aerosols

HEAT AND MOISTURE

FUEL MOISTURE

WRF Chem
- tracer dispersion
- chemistry of fire-emitted chemical species

WRF framework (atmosphere)
- ARW atmospheric core
- WPS preprocessing system

Fire Spread Model:
- Rothermel fire spread model
- Fire front tracking based on the level set method

Fuel Moisture Model
- drying and wetting due to changes in T and RH
- effects of precipitation

Fire Emission Model
- Emission of chemical species for GOCART, RADM2 and MOZART

LOCAL WINDS

AIR TEMPERATURE

RELATIVE HUMIDITY

PRECIPITATION

METEO OUTPUT

Standard weather forecast
- wind speed and direction
- air temperature
- air humidity
- precipitation
- cloudiness etc...

CHEM OUTPUT

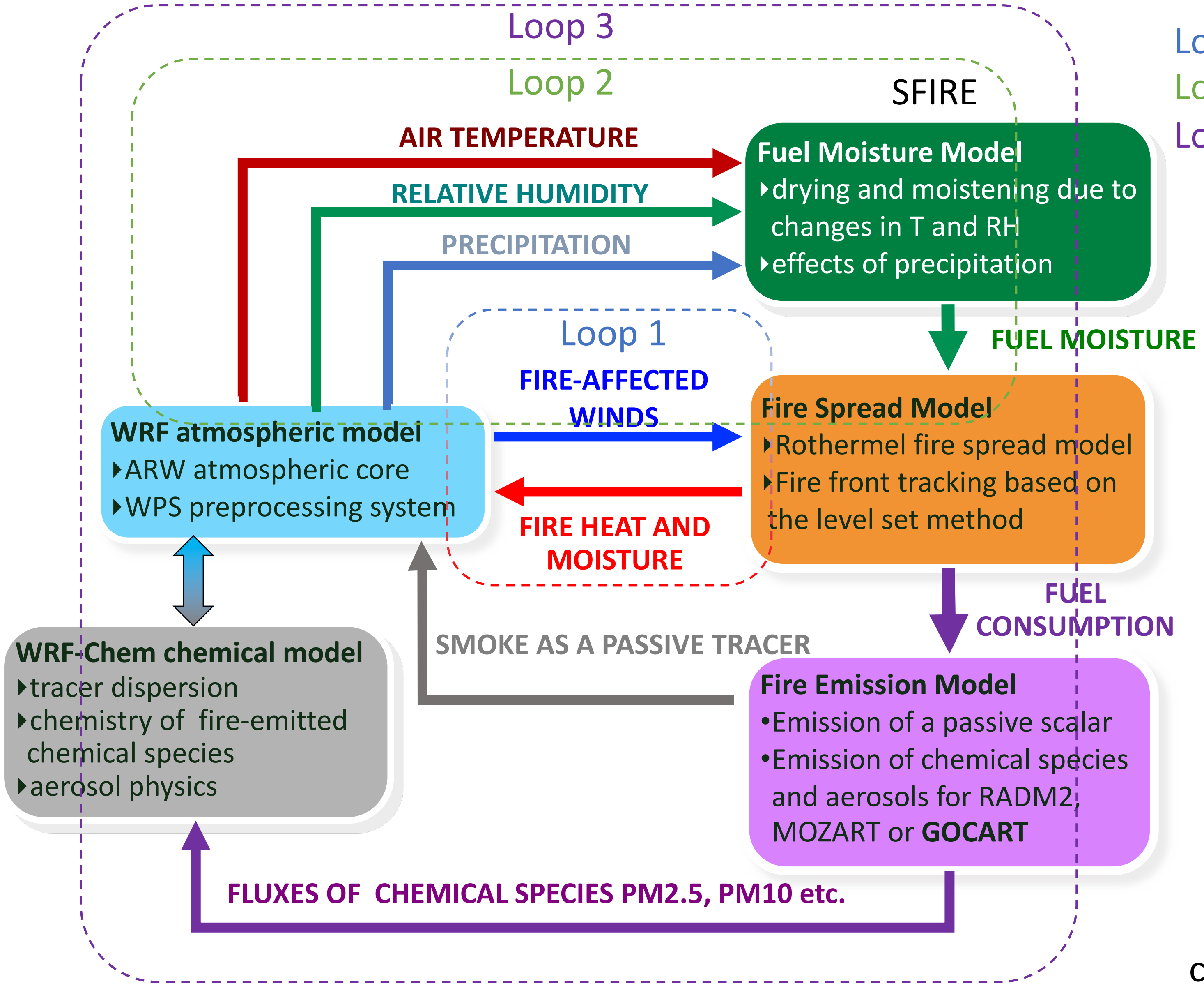
Wildland fire emissions and air quality forecast:
- smoke (tracer concentration)
- concentration of: RADM2/MOZART/GOCART species
- concentration of secondary pollutants (O_3 etc)

FIRE OUTPUT

High-resolution fire forecast:
- fire area
- fire heat flux
- fire intensity
- fire rate of spread
- fuel moisture

- Fire progression is simulated in-line with local meteorology
- Heat, moisture and **emission fluxes as chemical species** are computed based on the fire characteristics (geometry and intensity)
- Fire propagation is traced on a refined fire mesh typically 30m resolution using high resolution fuel maps and topography
- Plume dynamics and smoke dispersion are resolved on the model grid w/o external parametrizations
- On-line fuel moisture model resolves fluctuation in the fuel moisture due to changing weather conditions
- Inline chemical transport model resolves **chemical smoke transformations**

Fire-atmosphere coupling in WRF-SFIRE



Loop 3

Loop 2

SFIRE

AIR TEMPERATURE

RELATIVE HUMIDITY

PRECIPITATION

Fuel Moisture Model
- drying and moistening due to changes in T and RH
- effects of precipitation

FUEL MOISTURE

Loop 1

FIRE-AFFECTED WINDS

FIRE HEAT AND MOISTURE

WRF atmospheric model
- ARW atmospheric core
- WPS preprocessing system

Fire Spread Model
- Rothermel fire spread model
- Fire front tracking based on the level set method

FUEL CONSUMPTION

SMOKE AS A PASSIVE TRACER

WRF-Chem chemical model
- tracer dispersion
- chemistry of fire-emitted chemical species
- aerosol physics

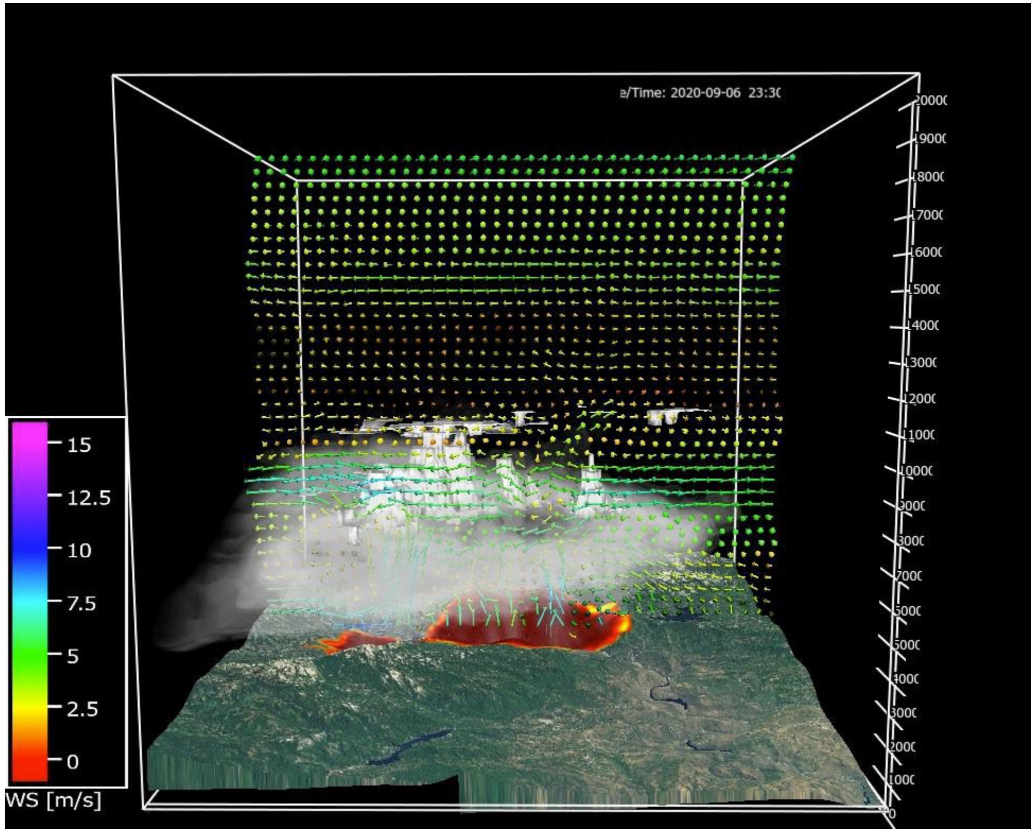
Fire Emission Model
- Emission of a passive scalar
- Emission of chemical species and aerosols for RADM2, MOZART or **GOCART**

FLUXES OF CHEMICAL SPECIES PM2.5, PM10 etc.

Loop 1: fire-induced winds and pyroconvection

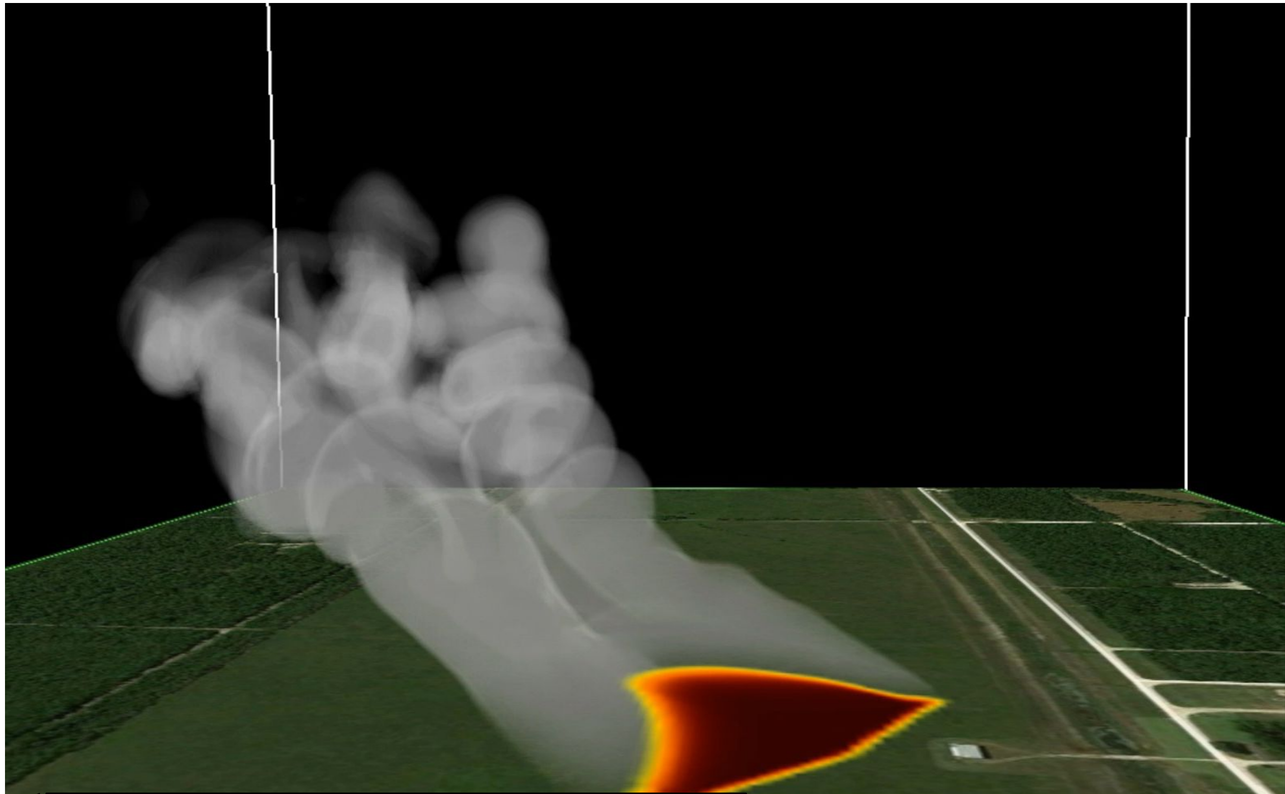
Loop 2: fuel moisture variations driven by meteorology

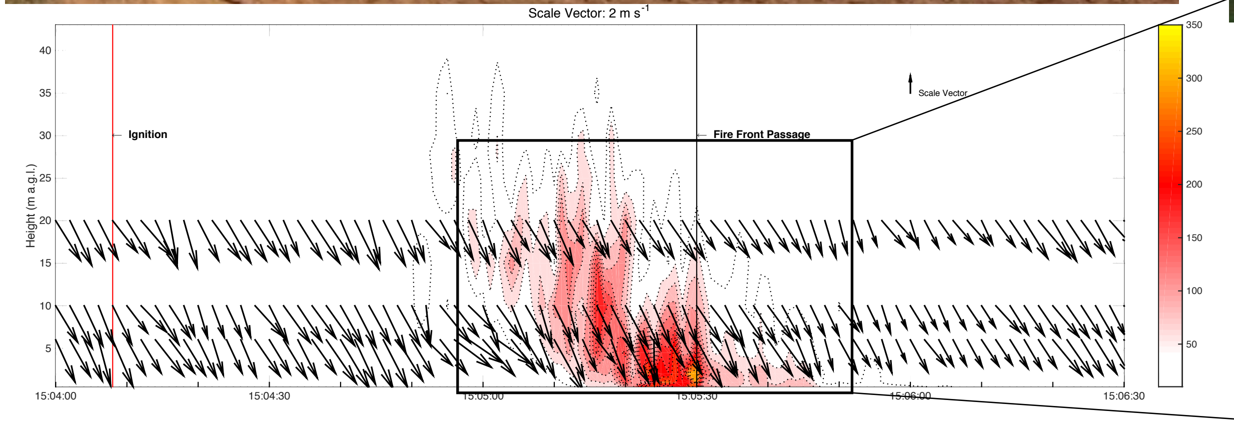
Loop 3. meteorological impacts of fire emissions

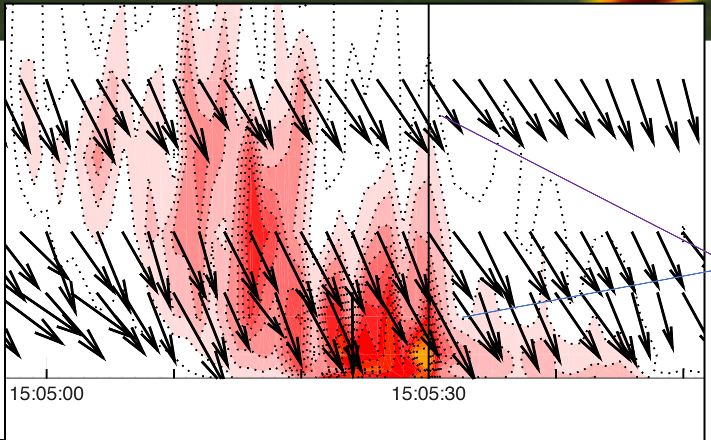


An example of a coupled fire-weather forecast capturing pyroCb formation during Creek Fire 2020

Fire impacts on near-surface winds during the FireFlux II experiment





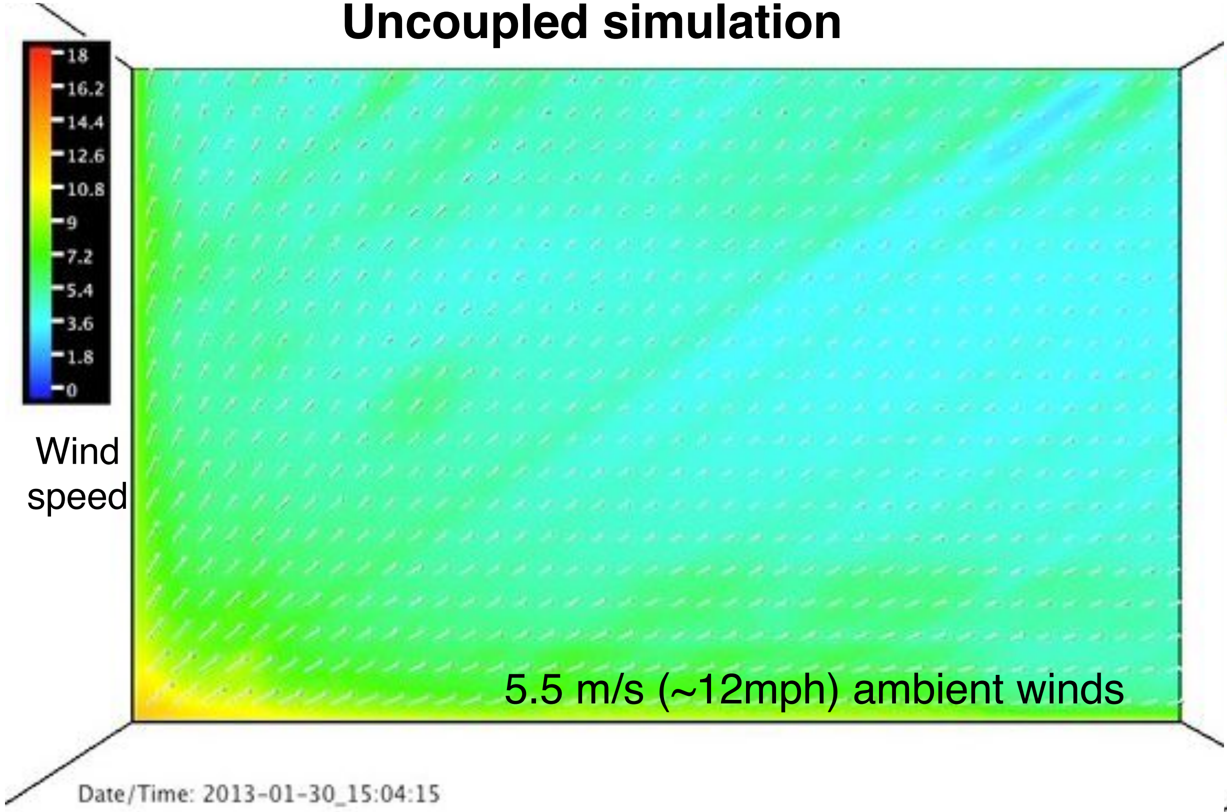


Winds aloft are weaker than at the surface during the fire front passage

Clements et al. 2019

Fire modifies local circulation and accelerates near-surface winds

Uncoupled simulation

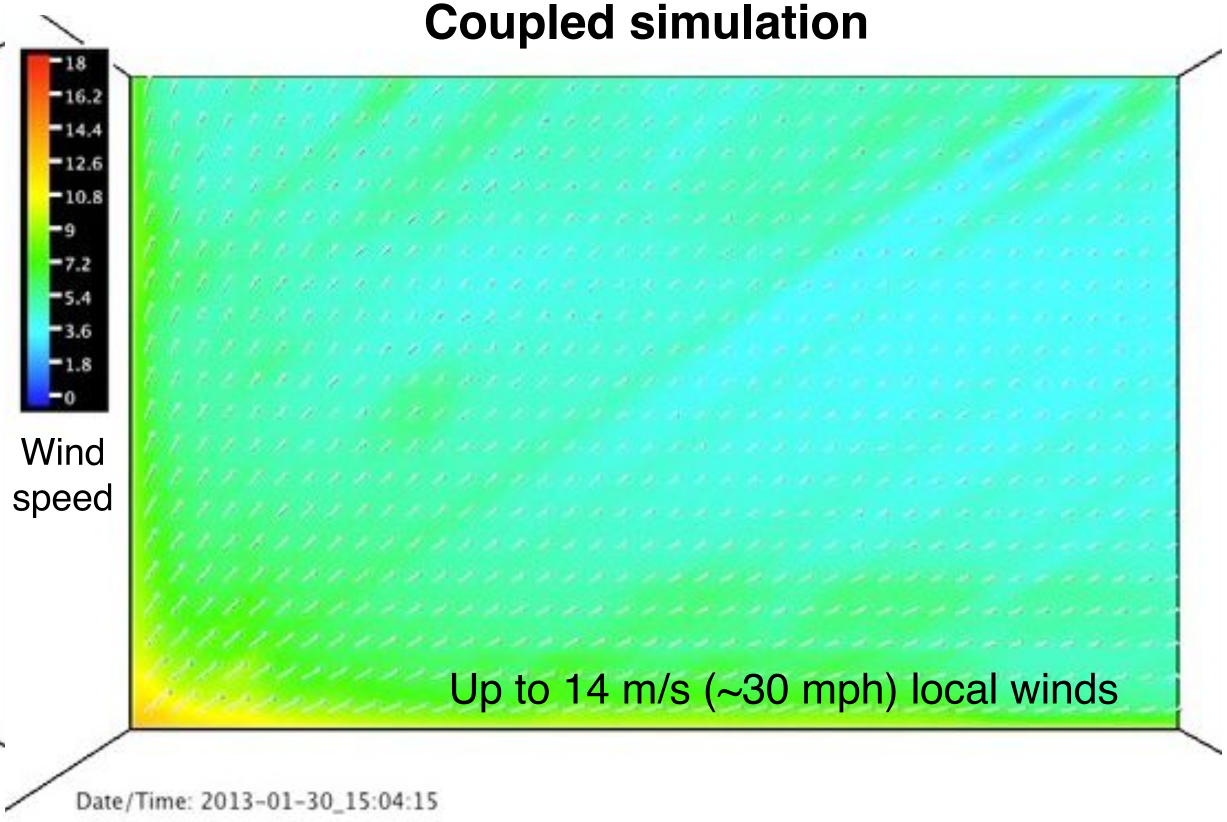


Wind speed

5.5 m/s (~12mph) ambient winds

Date/Time: 2013-01-30_15:04:15

Coupled simulation



Wind speed

Up to 14 m/s (~30 mph) local winds

Date/Time: 2013-01-30_15:04:15

Fire-atmosphere interactions can significantly alter local winds and fire behavior

- Uniform winds are not disturbed by the fire
- Slower fire propagation

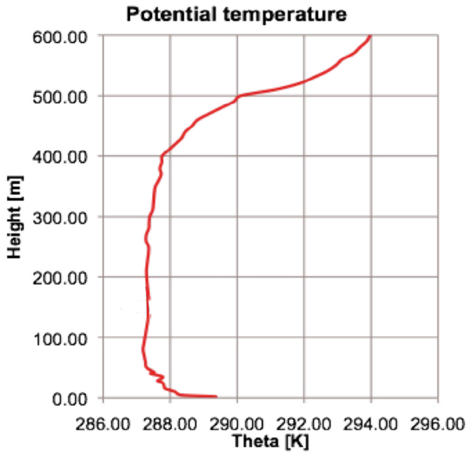
- Highly variable local winds
- Faster fire propagation

Investigation of the fire-induced flow during a grass burn

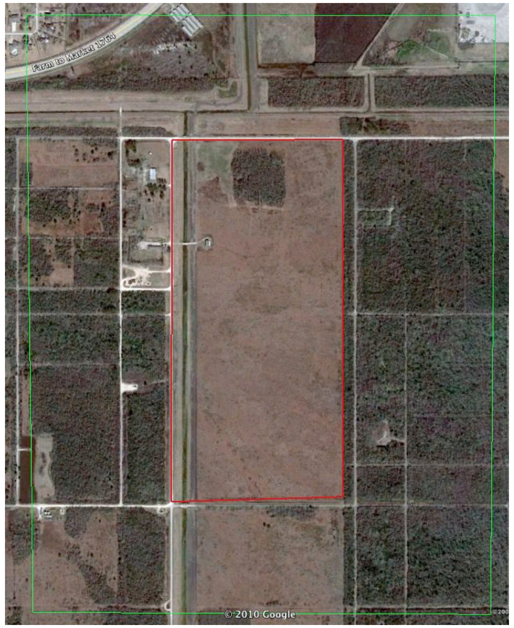
FireFlux prescribed burn of 155 acres (0.63 km^2) prairie

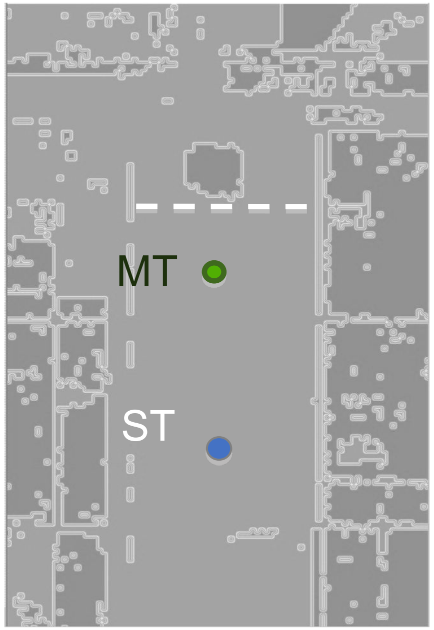
Model setup:

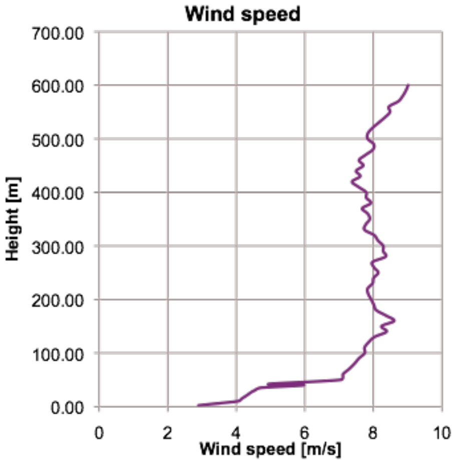
- 1 domain, 1000m x 1600m, 10m horizontal resolution
- 80 vertical levels from 2-1200m AGL
- Fire grid resolution – 1m
- Input: vertical profiles of temperature, moisture and wind, fuel type, height and fuel moisture
- Output: integrated 3D representation of the atmospheric conditions and 2D representation of the fire front.

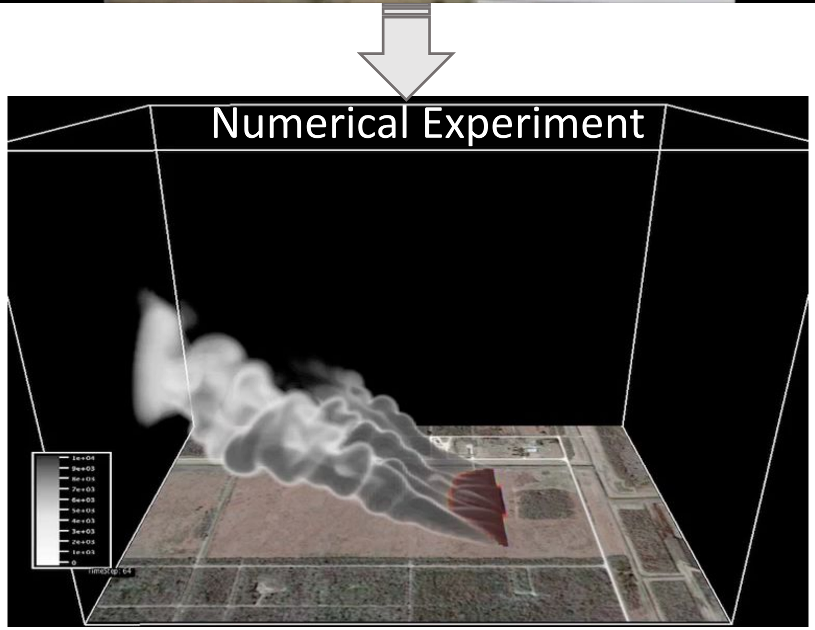


Field Experiment







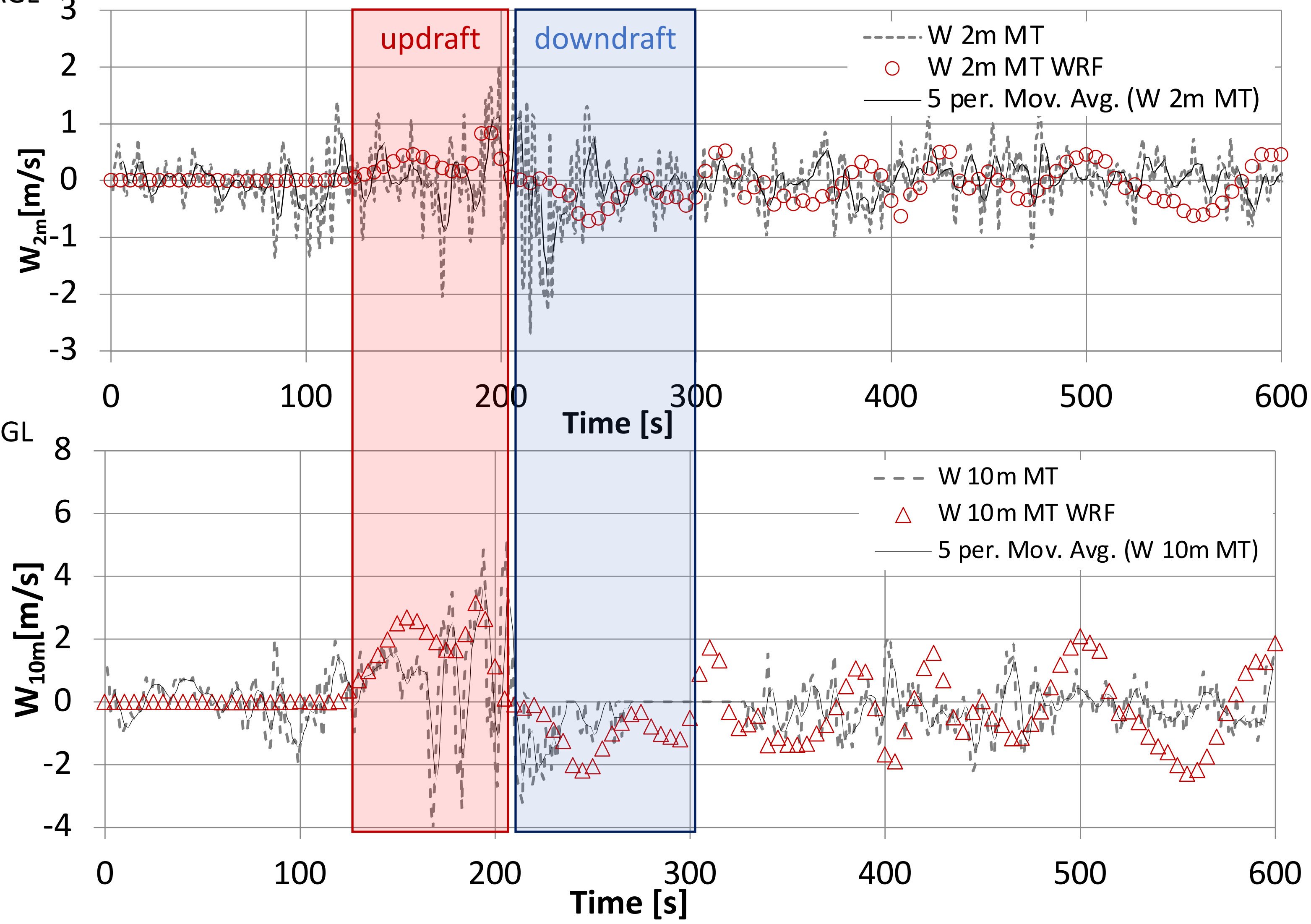


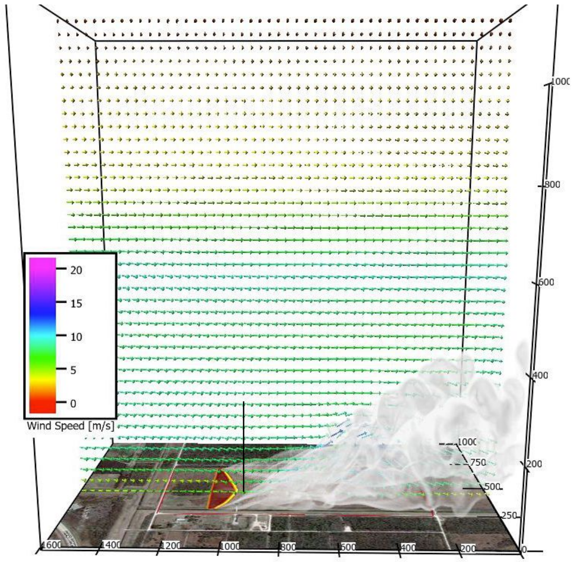
FireFlux experiment Clements et al. 2008

Vertical winds induced by the passing fire front

Updraft at 2m AGL
(Main Tower)

Updraft at 10m AGL
(Main Tower)

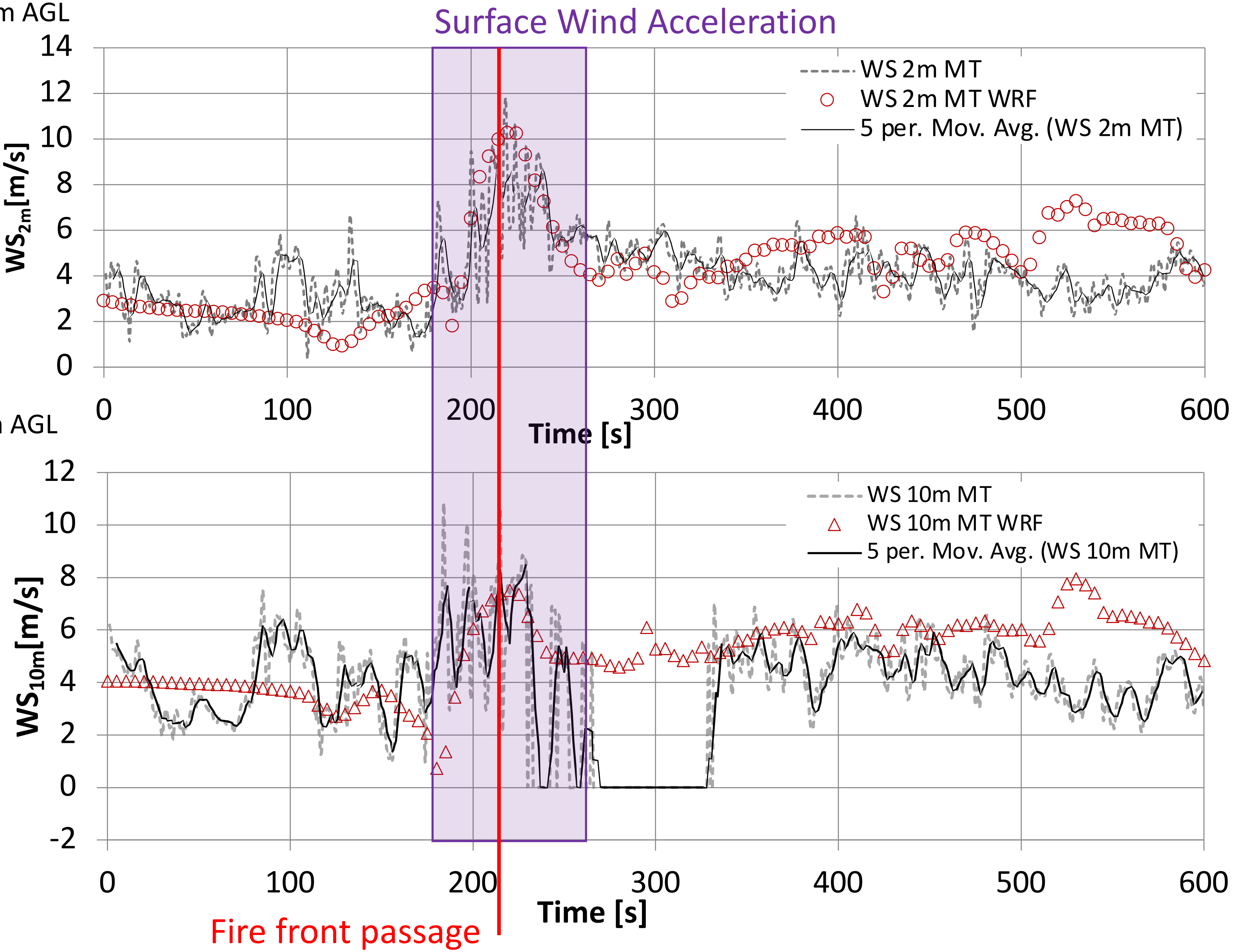




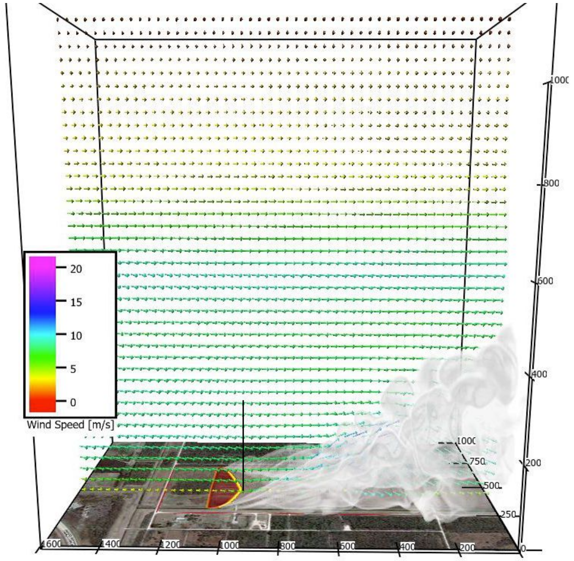
Fire-induced horizontal winds

Wind speed at 2m AGL
(Main Tower)

Wind speed at 10m AGL
(Main Tower)

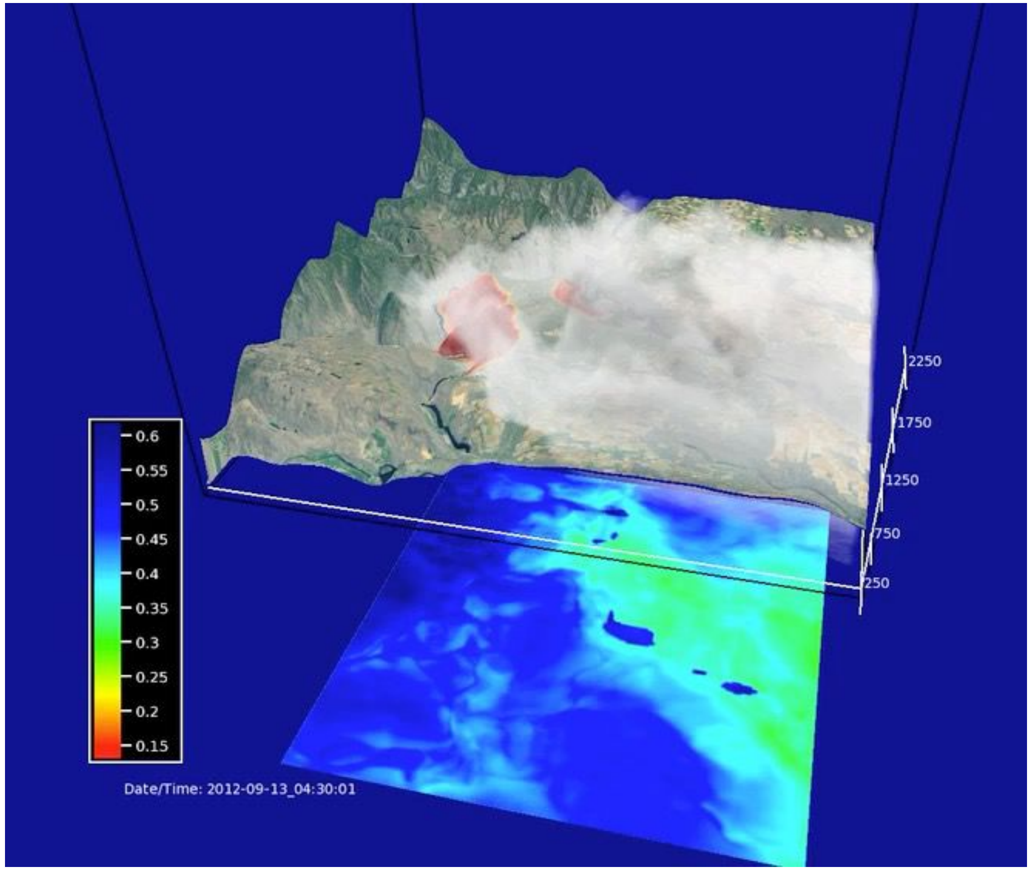


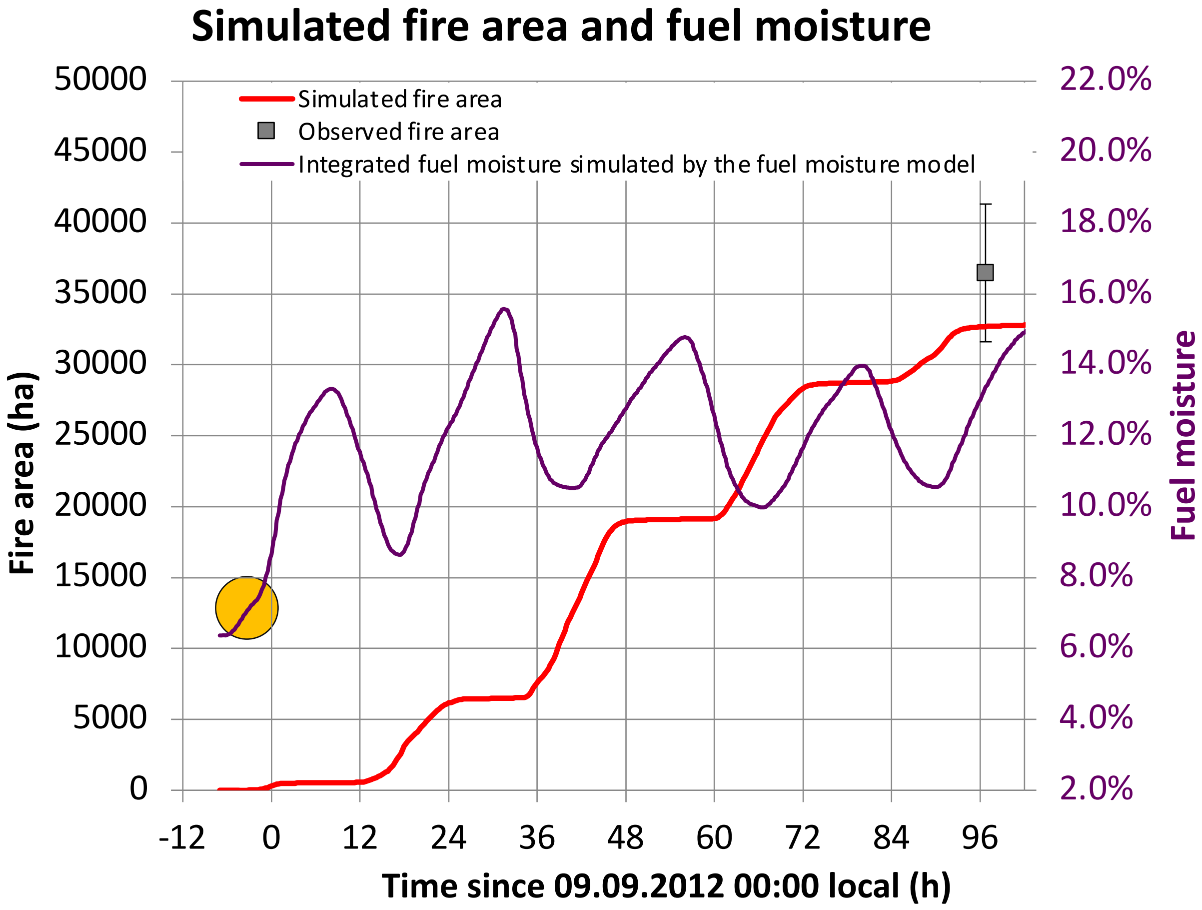
During the fire front passage winds at 2 m are greater than at 10 m



Coupling between weather and fuel moisture impacts fire activity

Barker Canyon Fire (WA 2012) 29,000 acres



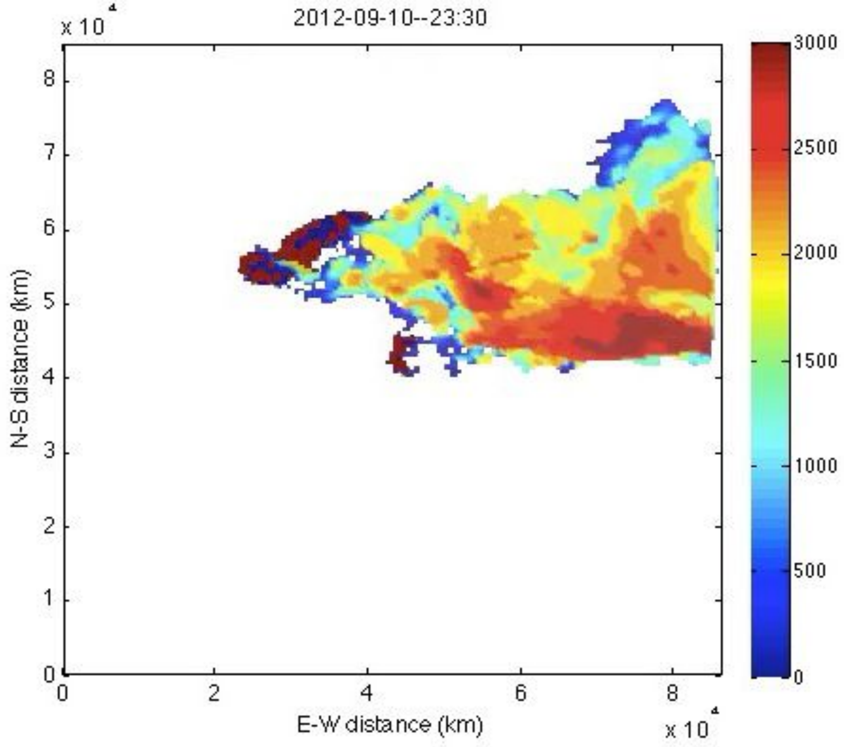


- Daytime warming decreases fuel moisture while nighttime cooling increases it.
- Diurnal fluctuations in temperature and fuel moisture make fire active during the daytime (low fuel moisture) and stagnant during the nighttime (high fuel moisture).

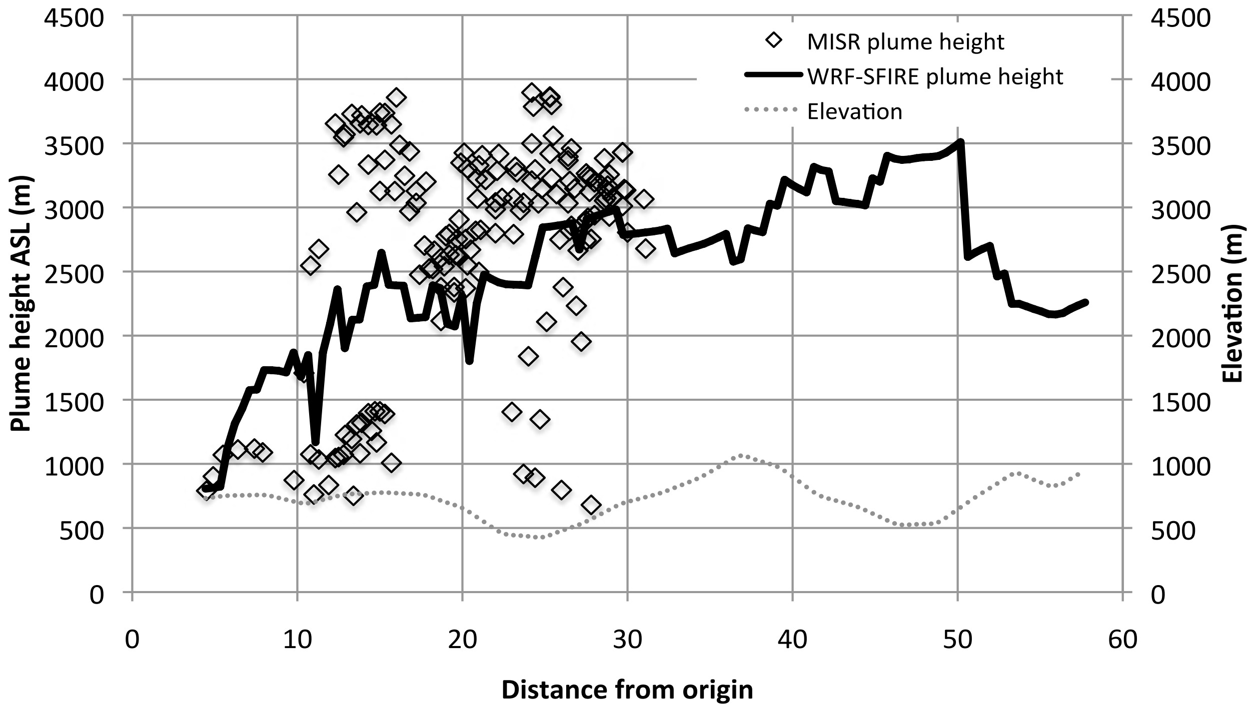
Coupling between weather and fuel moisture impacts plume rise

An example of a coupled fire-atmosphere Simulation of Barker Canyon Fire (WA 2012)

Simulated plume top height



MISR (observed) plume top height vs simulated plume top height



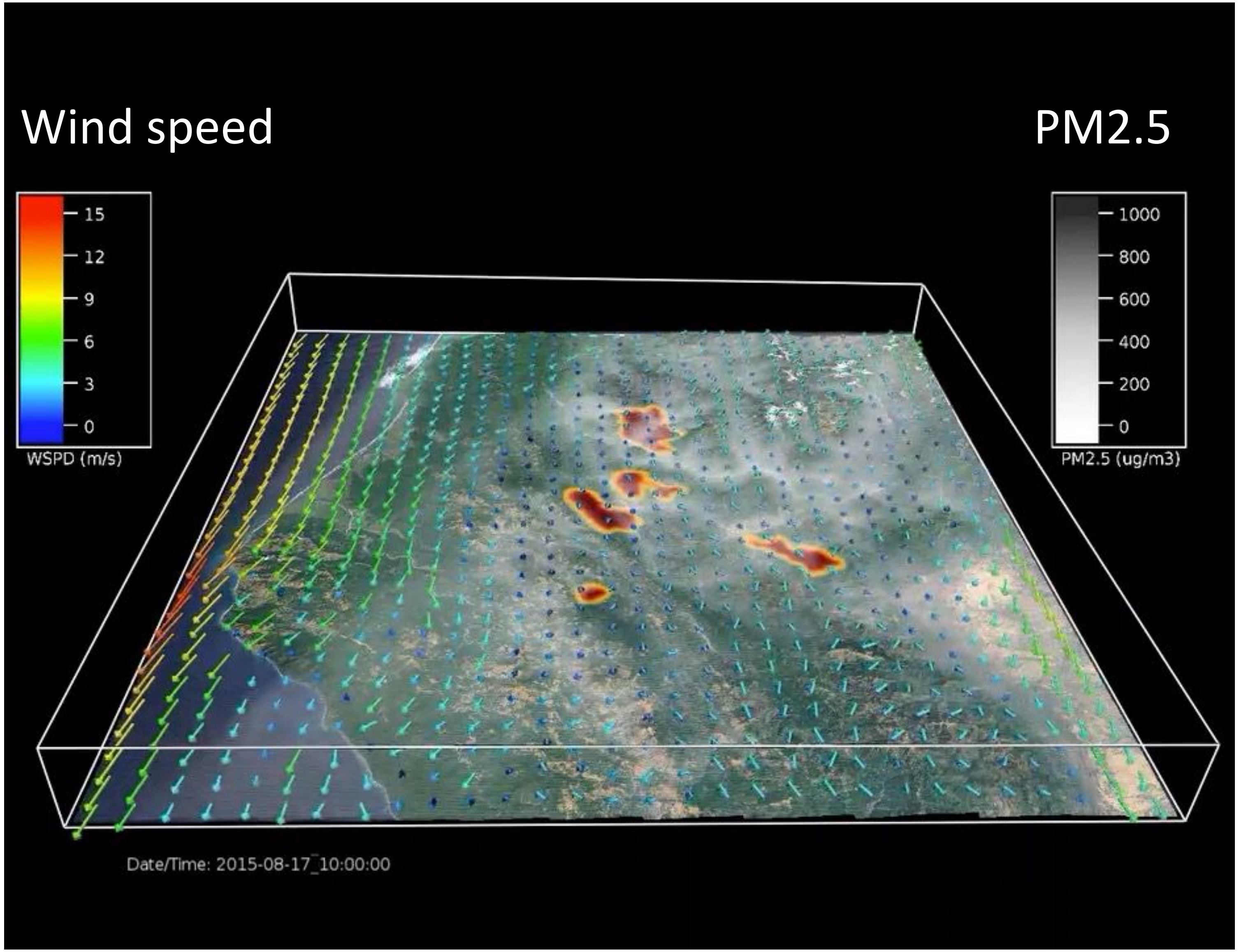
Changes in the dead fuel moisture impact fire intensity and plume dynamics. Periods of lower fuel moisture content correspond to more active fire, stronger updrafts and taller plumes

Coupled simulations accounting for radiative impacts of smoke

- We run WRF-SFIRE coupled simulations for August 2015 CA Fires

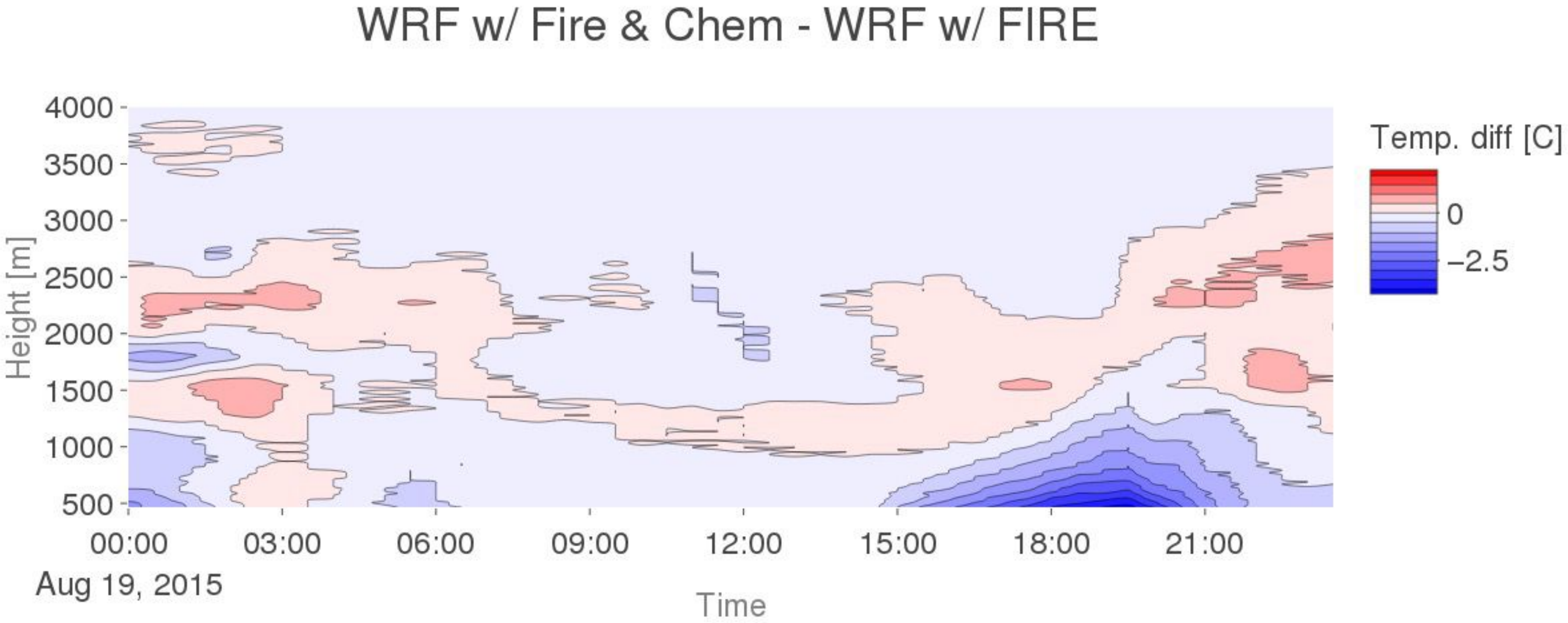
- We simulate 5 fires in domain 3 at 1.3km resolution, and one in domain 2 at 4km resolution

- Emissions from these fires interact through the GOCART aerosol scheme with atmospheric radiation, in order to account for primary radiative effects of fire smoke.



Thermal effects of smoke

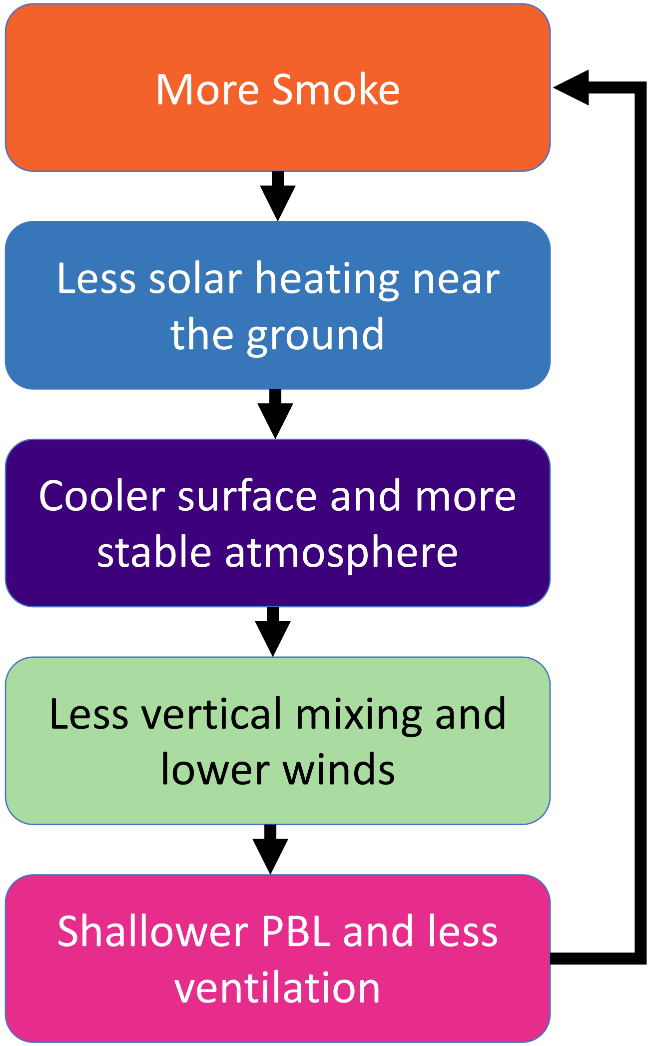
Vertical c-section showing the thermal structure impacted by radiative smoke impacts



Differences in vertical temperature profiles between the WRF-SFIRE simulation with and without radiative smoke effects reveals daytime warming aloft and cooling at the surface, which increases atmospheric stability, enhances local inversions and inhibits ventilation of smoke trapped in the valleys.

Radiative impacts of smoke from wildland fires

Positive feedback mechanism:



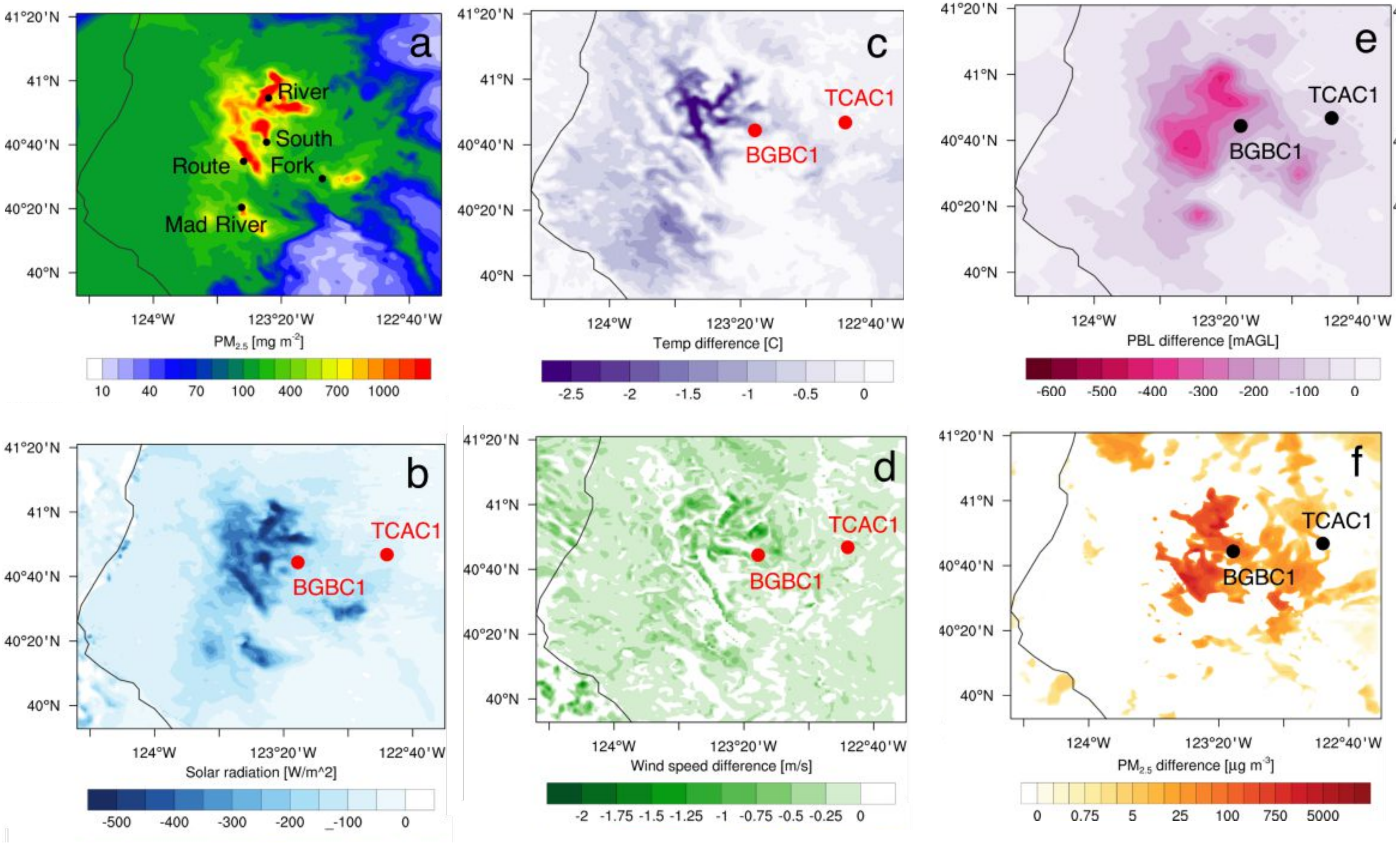
More Smoke

Less solar heating near the ground

Cooler surface and more stable atmosphere

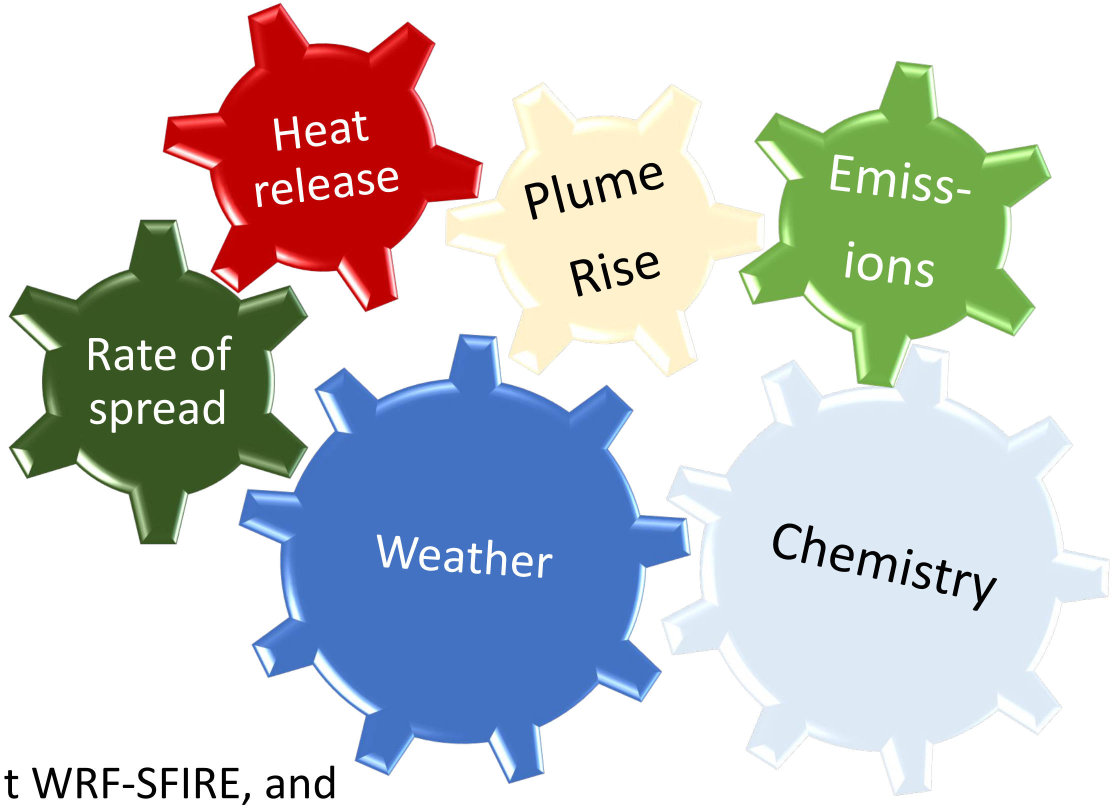
Less vertical mixing and lower winds

Shallower PBL and less ventilation



QUESTIONS?

Fire-atmosphere coupling processes in WRF-SFIRE:
Loop 1: fire-induced winds and pyroconvection
Loop 2: fuel moisture variations driven by meteorology
Loop 3. meteorological impacts of fire emissions



Visit:
https://www.openwfm.org to download the code and learn about WRF-SFIRE, and
https://demo.openwfm.org/sj/ for near real time fuel moisture analysis based on RAWS data
https://www.met.sjsu.edu/ak to check my personal website
https://www.sjsu.edu/wildfire/research/modeling.php to meet the Wildfire Interdisciplinary Research Center fire modeling group

e-mail: Adam.Kochanski@sjsu.edu