Fire-Atmosphere Interactions at multiple scales

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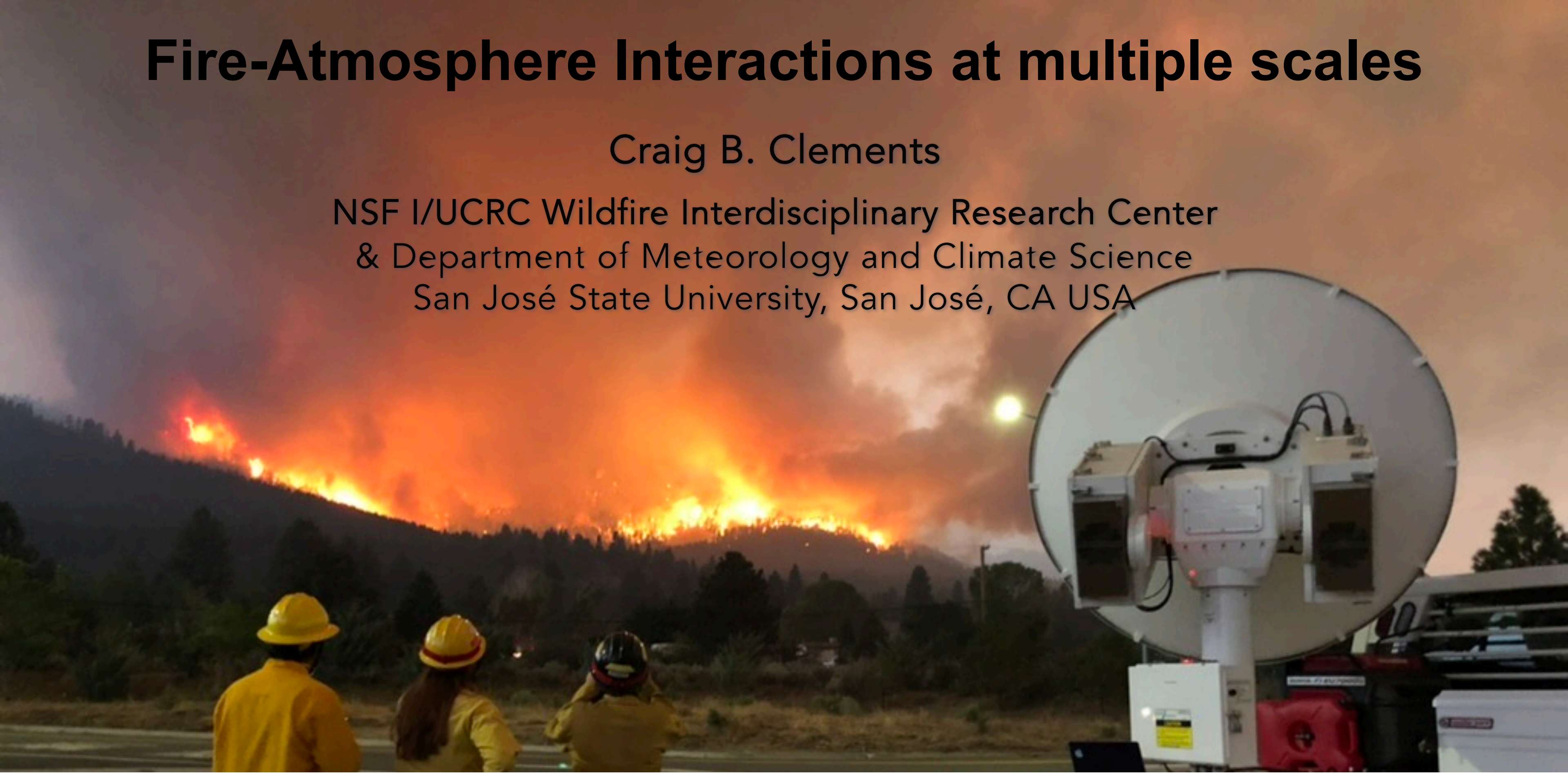


Burgers Program and Combustion Institute Summer School
on Fire Safety Science – Wildland/WUI Fire Behavior

SJSU SAN JOSÉ STATE UNIVERSITY

WIRC Wildfire Interdisciplinary Research Center

Outline

- **Fire-Atmosphere interactions at small scales**
  - - turbulence processes
  - - fire-induced circulations
  - - Role of small-scale field experiments

- **Processes in large wildfires**
  - - Plume structures and plume dynamics
  - - Ordinary plumes and pyroCb
  - - anomalous cases: smoke shading

- **Impacts of complex terrain on fire behavior**
  - Some examples

Motivation

Fires are becoming more extreme, yet we don’t fully understand the dynamics of fire-atmosphere interactions and what role these have on fire behavior.

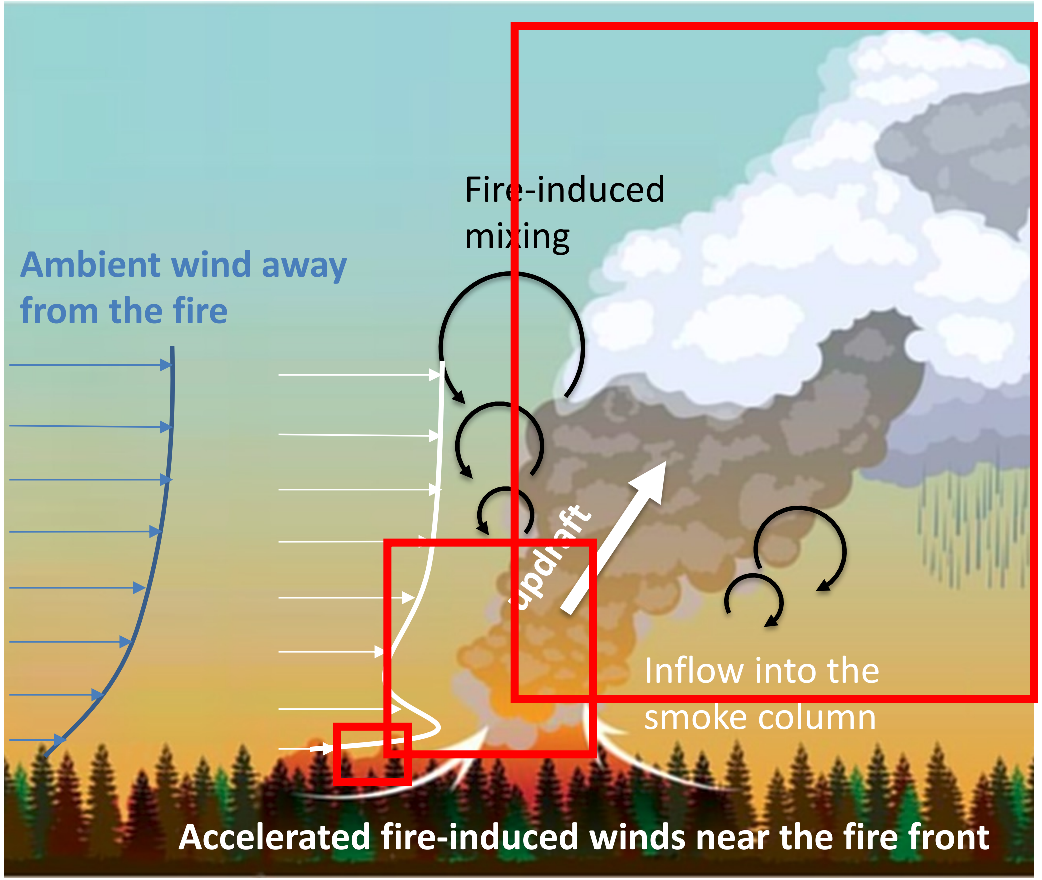
Carr Fire Tornado (EF-3)
Redding, California
26 July 2018

Fire-atmosphere Interactions

Potter (2012): interactions between fuels presently burning and atmosphere, and

interactions between the atmosphere and fuels that will eventually burn in a given fire.

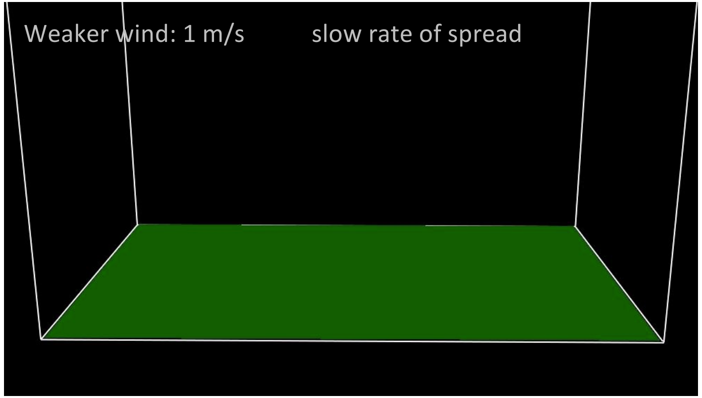
FAI as long as the fire-induced perturbations in state variables are greater than ambient variability.



Idealized framework for extreme fire behavior

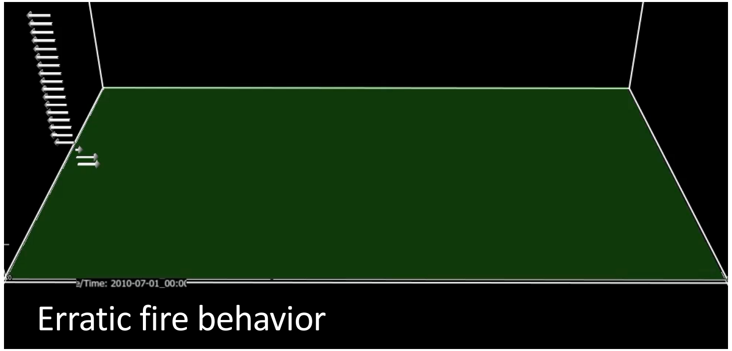
WRF-SFIRE simulations courtesy of Adam Kochanski

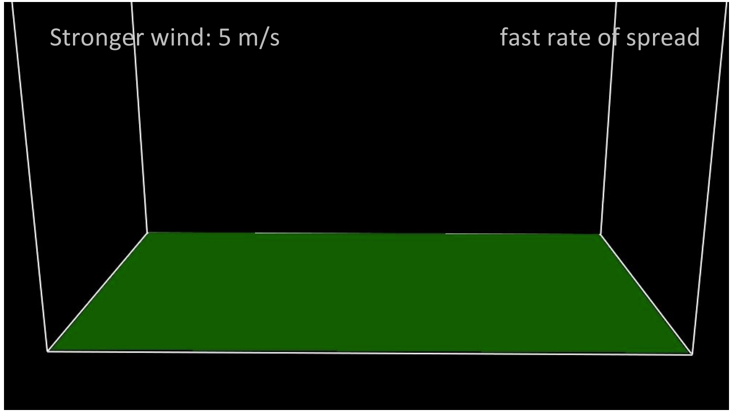
- Idealized grass fire experiments
- More narrow head fire front with stronger wind speed
- Erratic fire behavior with strong directional shear.



More vertical smoke column slower fire progression

surface wind decoupled from the opposite upper flow



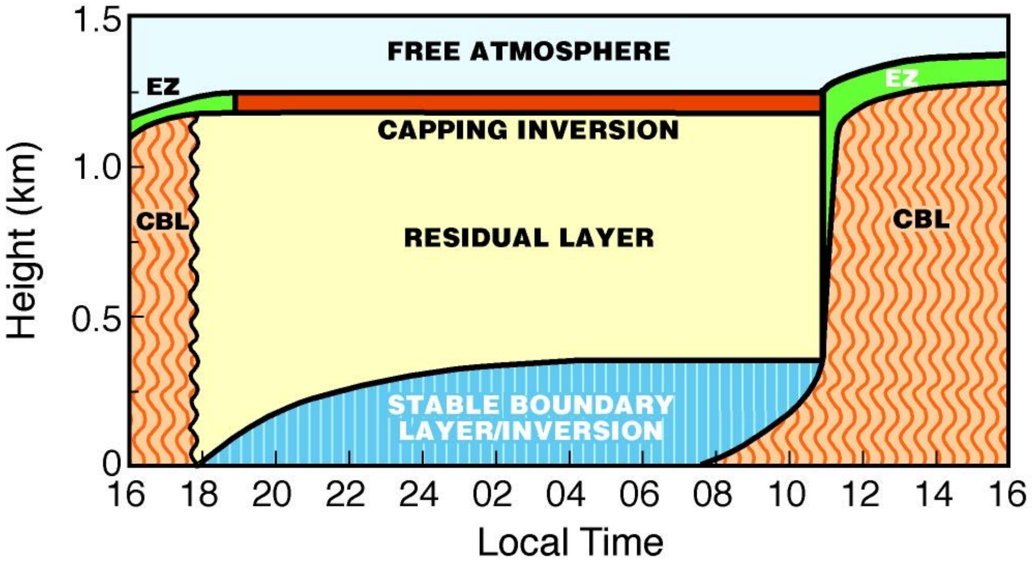


More tilted smoke column faster fire progression

Planetary Boundary Layer

The layer of air influenced by surface friction is called the planetary boundary layer (PBL).

Define the boundary layer as that part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of ~ 1 hr or less.



Sun et al. 2009

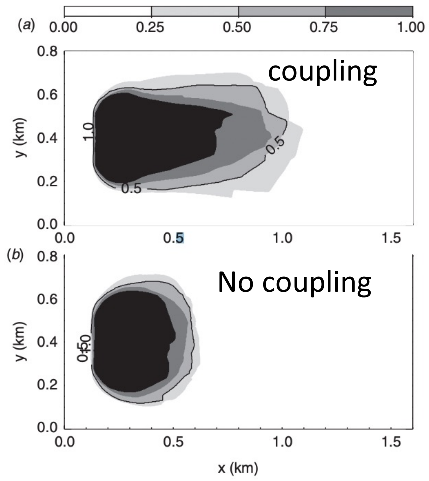


Fig. 10. Burn probabilities based on 24 fires in the convective boundary layer (CBL) at 5 min after the fires started: upper plot (*a*) is the 'two-way coupled' case; lower plot (*b*) is the 'one-way coupled' case. Initial fire line length (L_{ig}) was 200 m.

Background: definitions

What is turbulence?

- Simply defined as **perturbation from the mean**.

$$u = (\overline{u} + u') \qquad u' = u - \overline{u}$$

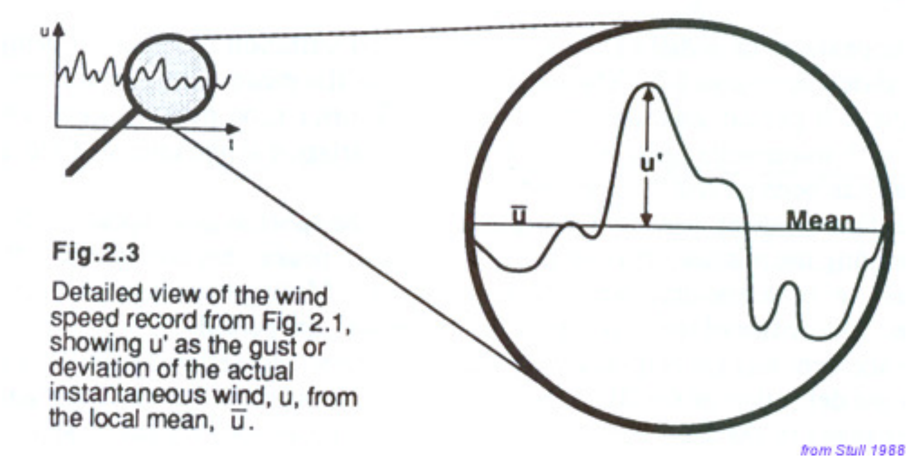


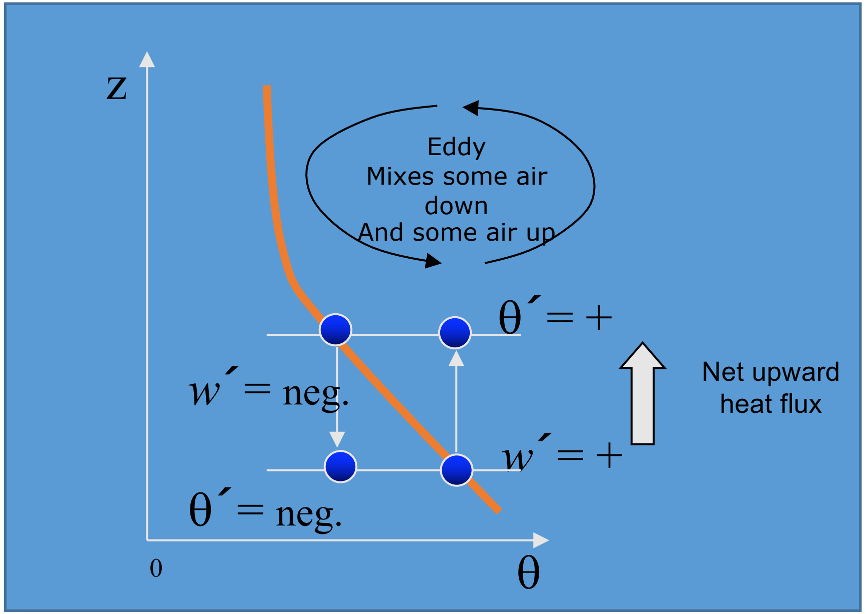
Fig.2.3

Detailed view of the wind speed record from Fig. 2.1, showing u' as the gust or deviation of the actual instantaneous wind, u, from the local mean, $\overline{u}$.

Turbulent Flux?

- Transport of a quantity by eddies or swirls.
- The covariance of a velocity component and any quantity.

$$\mathrm{cov}(w\theta) = \frac{1}{N}\sum_{i=0}^{N-1}(W - \overline{W})\cdot(\theta - \overline{\theta}) = \frac{1}{N}\sum_{i=1}^{N} w_i'\theta_i' = \overline{w'\theta'}$$



Turbulent Sensible Heat Flux

$$H_s = \overline{\rho} c_p \overline{w'T'}$$

3-D Sonic Anemometer

Micrometeorology of the fire front and near surface environment

- Fire front passage (FFP)
- Fire-induced winds

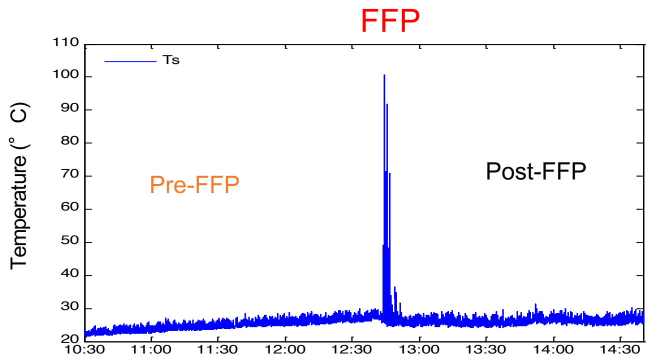
FireFlux Experiment (Clements et al. 2007)

Structure of Fire Front Passage (FFP)

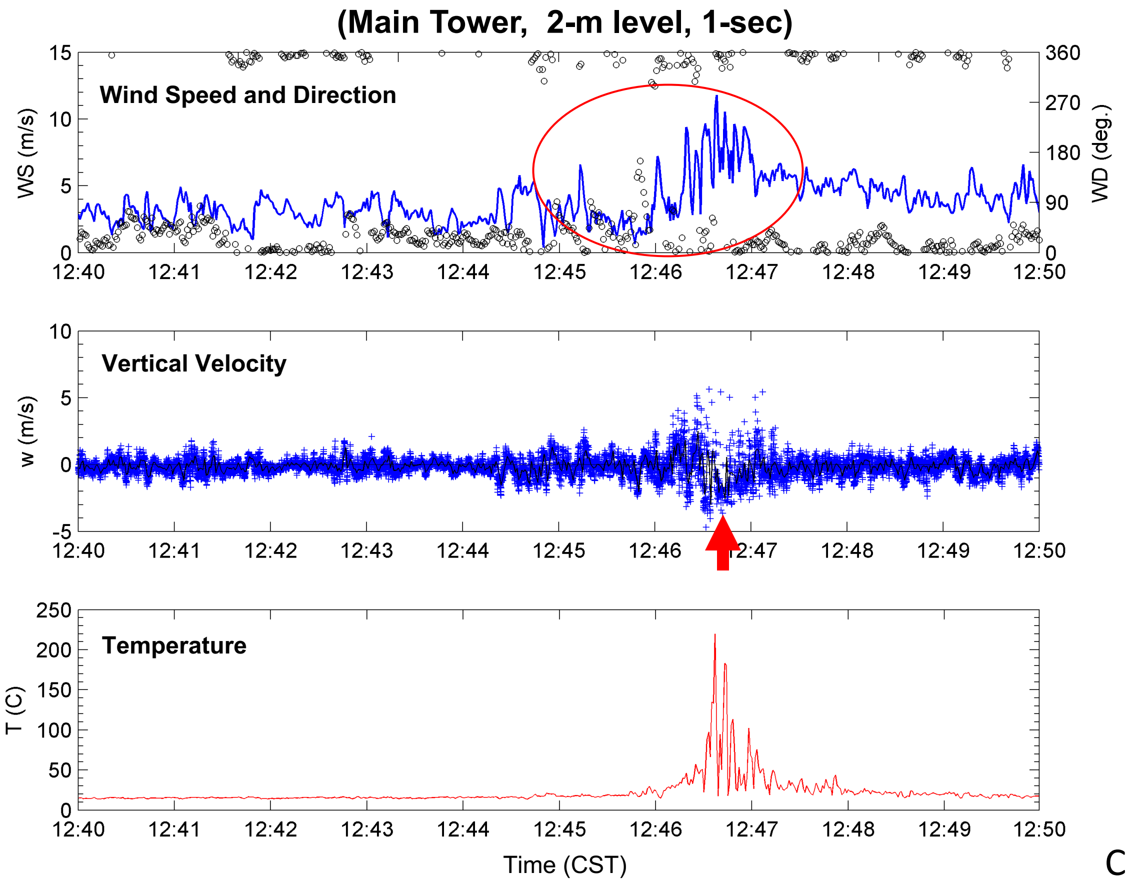
To better characterize the micrometeorology of the fire front, the period of Fire Front Passage was defined (Clements et al. 2008).

The FFP is characterized by

- Increase in velocity field *u, v, w*, and temperature, *T*.
- Surface wind reversal.
- Peak in turbulence and sensible heat flux.
- Minimum in atmospheric pressure.
- Strength of each determines Fire-Atmosphere coupling.



Fire Front Passage and Fire-Induced Surface Winds



Clements *et al*. (2007)

Observations of atmospheric surface pressure and vertical velocity during fire front passage

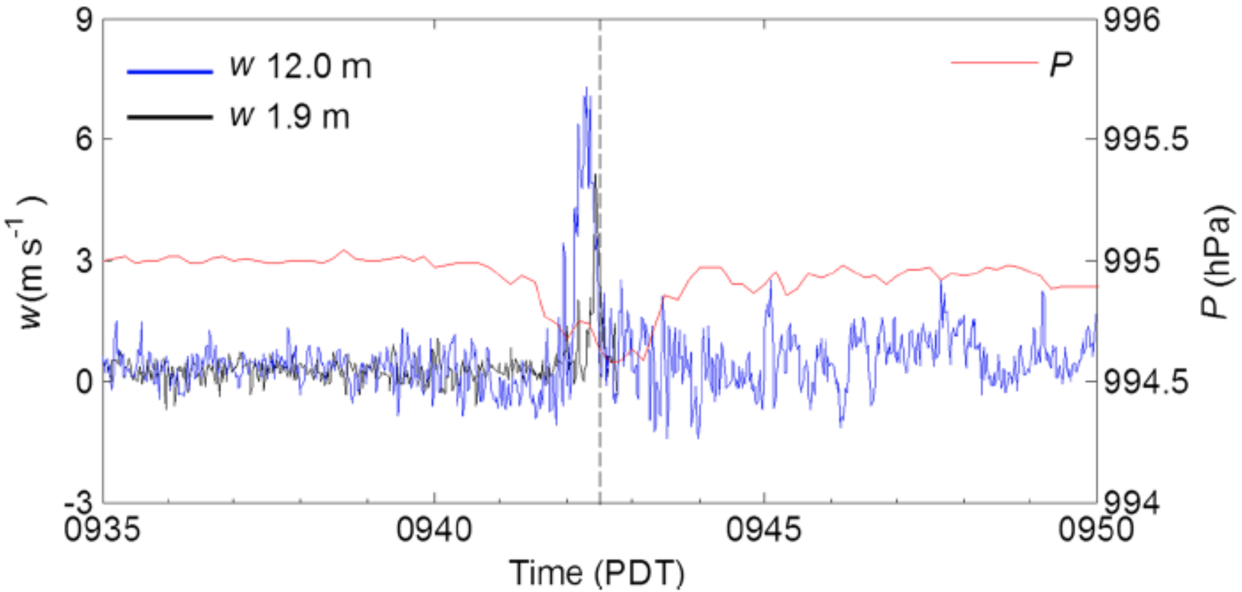
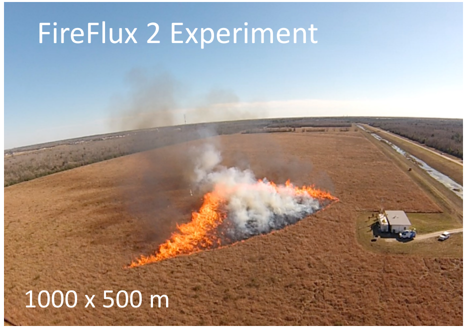
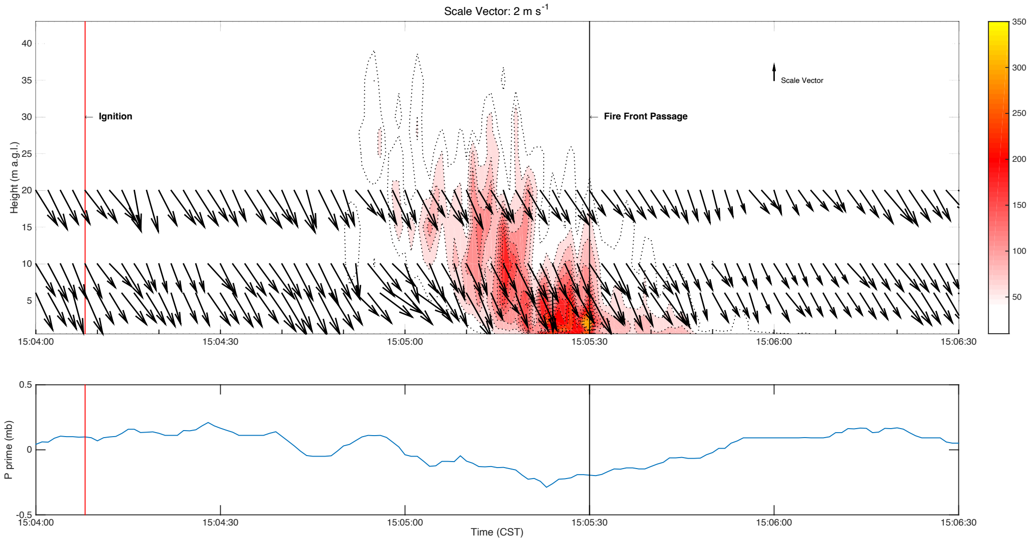


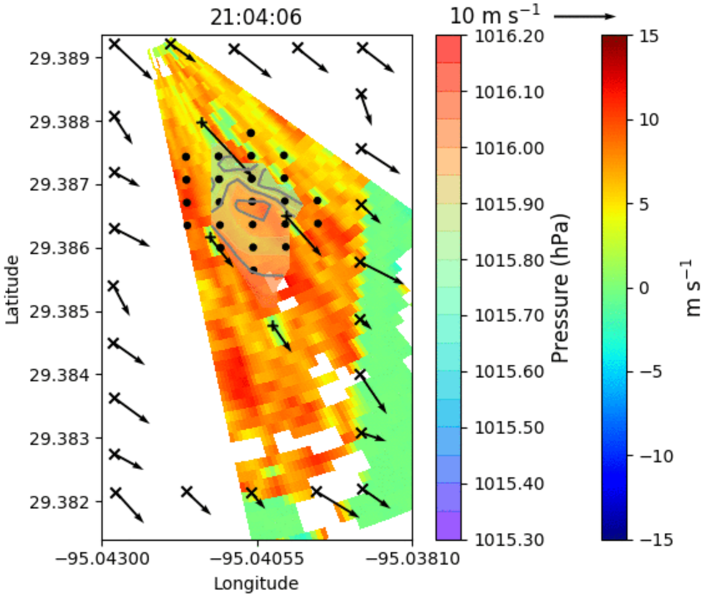
Fig. 10 Time series of atmospheric pressure *P* and vertical velocities *w* measured at the tower. *Black dashed line* indicates time of fire-front passage

Clements and Seto (2015)

FireFlux2: Surface pressure perturbations and fire-induced winds







- The advection of combustion gases ahead of fire front causing the ignition of fuels.
- Winds accelerate through the fire front due to the dynamic pressure perturbation.

Clements et al. (2019)

Observations of Fire-atmospheric interactions over slope with a cross wind.
(California, grass fuels, 24 June 2010)

Clements and Seto (2015)

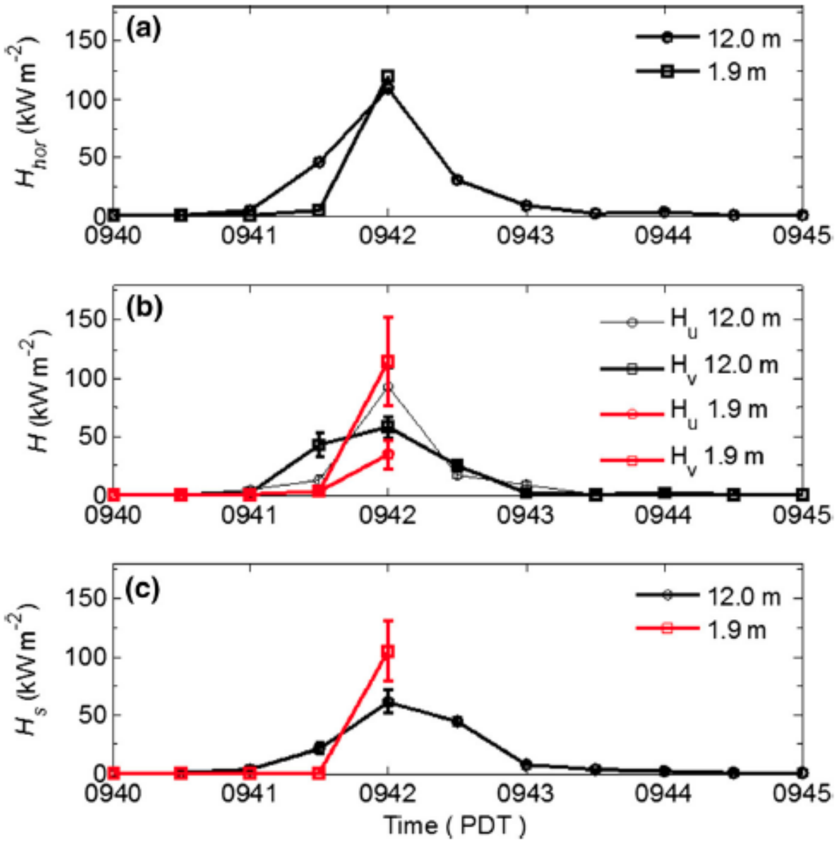
Measured Horizontal and Vertical Heat Fluxes over Slope

Turbulent Sensible Heat Flux (Vertical):

$$H_s = \overline{\rho} c_p \overline{w'T'}$$

Turbulent Horizontal Heat Flux:

$$H_{hor} = \overline{\rho} c_p \left[\left(\overline{u'T'} \right)^2 + \left(\overline{v'T'} \right)^2 \right]^{1/2}$$



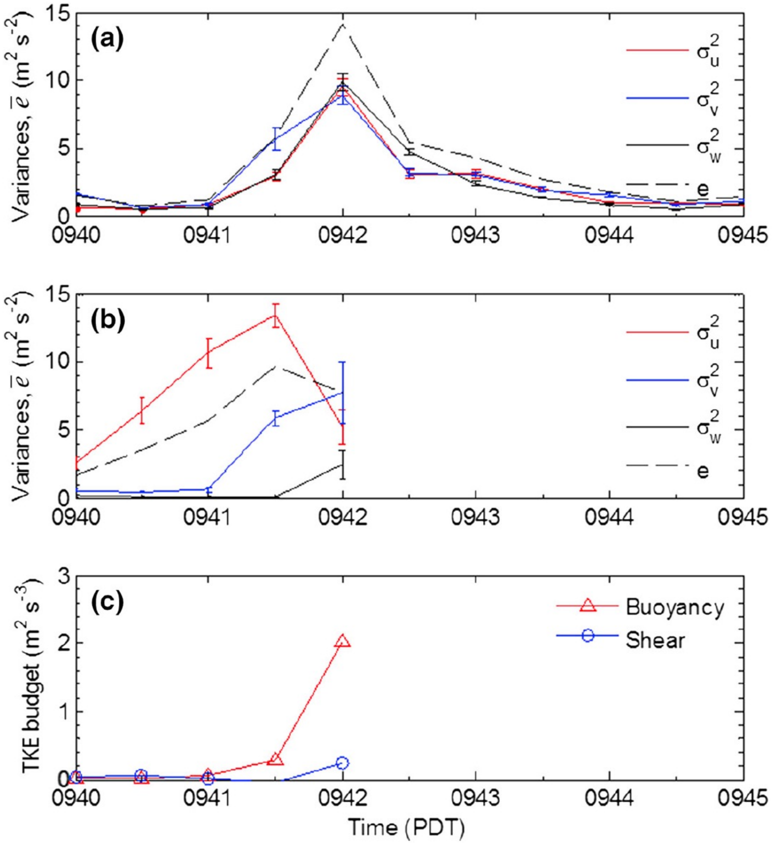
Clements and Seto (2015)

Turbulent Kinetic Energy Budget

$$\frac{\partial \bar{e}}{\partial t} = \frac{g}{T_V}\overline{w'T_V'} - \overline{u'w'}\frac{\partial \bar{U}}{\partial z} - \frac{\partial \overline{w'e}}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial \left(\overline{w'p'}\right)}{\partial z} - \varepsilon.$$

I	II	III	IV	V
buoyancy production	*shear production*	*turbulence transport*	*pressure correlation*	*dissipation*

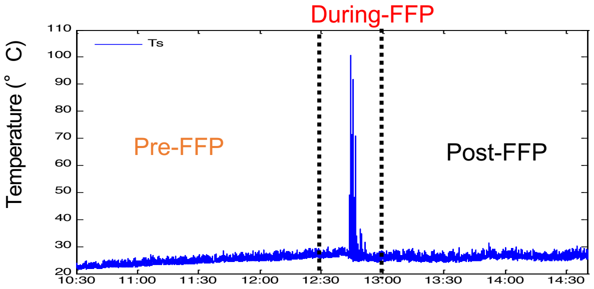
- Buoyancy production increased during fire-front passage due to a large increase in the sensible heat flux.
- The buoyancy production is larger in magnitude than the shear generation indicating that the production of turbulence is characteristic of free convection near and above the fire front—despite moderate wind.

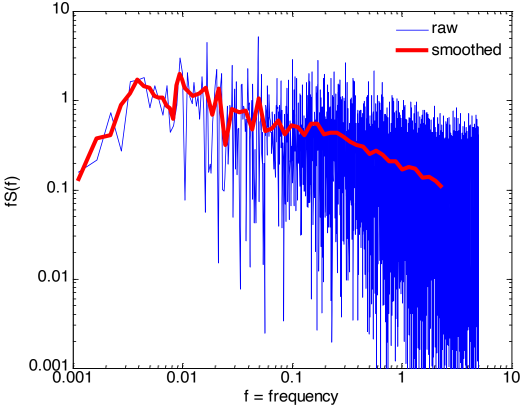


Clements and Seto (2015)

Data Processing: Turbulence Spectra

- Wind velocity and temperature (10 Hz):
  - U: rotated mean wind direction
  - V: rotated lateral wind direction
  - W: tilt-corrected, vertical velocity
  - Ts: sonic temperature
- Define Pre-, During-, Post-**Fire Front Passage** (**FFP**)
- Spectra were calculated every 30 min,
- Morlet Wavelet Transform or FFT





Monin-Obukhov Similarity Theory

Normalizing both axes appropriately, the spectra from a variety of conditions collapse into a single family of curves.

Shape dependent only on **Monin-Obukhov stability parameter**:

$$z/L = -\frac{(g/\bar{\theta})(\overline{w'\theta'})}{u_*^3/kz}$$

Scaling parameters:

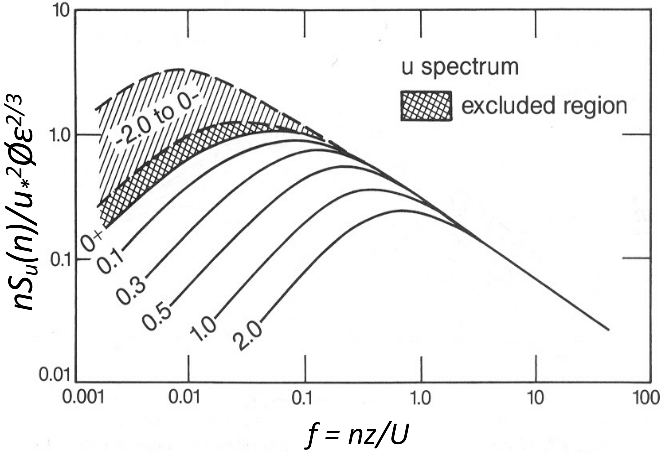
$$u_* = \left[(\overline{u'w'})^2 + (\overline{v'w'})^2\right]^{1/4}$$

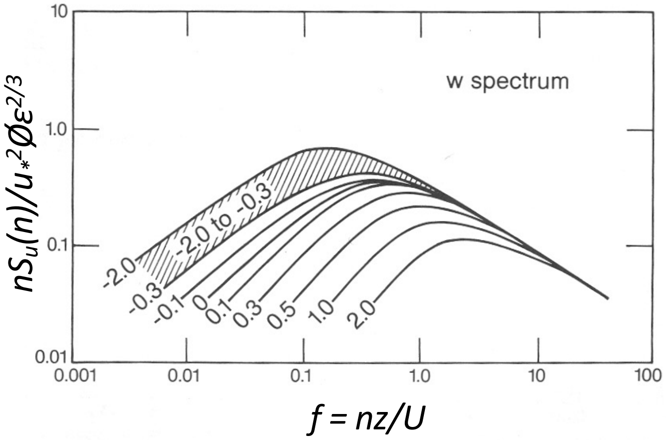
$$T_* = -\frac{\overline{w'T'}}{u_*}$$

φ_w and φ_T represent universal functions.

z: measurement height
L: Obukhov length
k: von Karman constant (0.4)

Kaimal and Finnigan (1994)

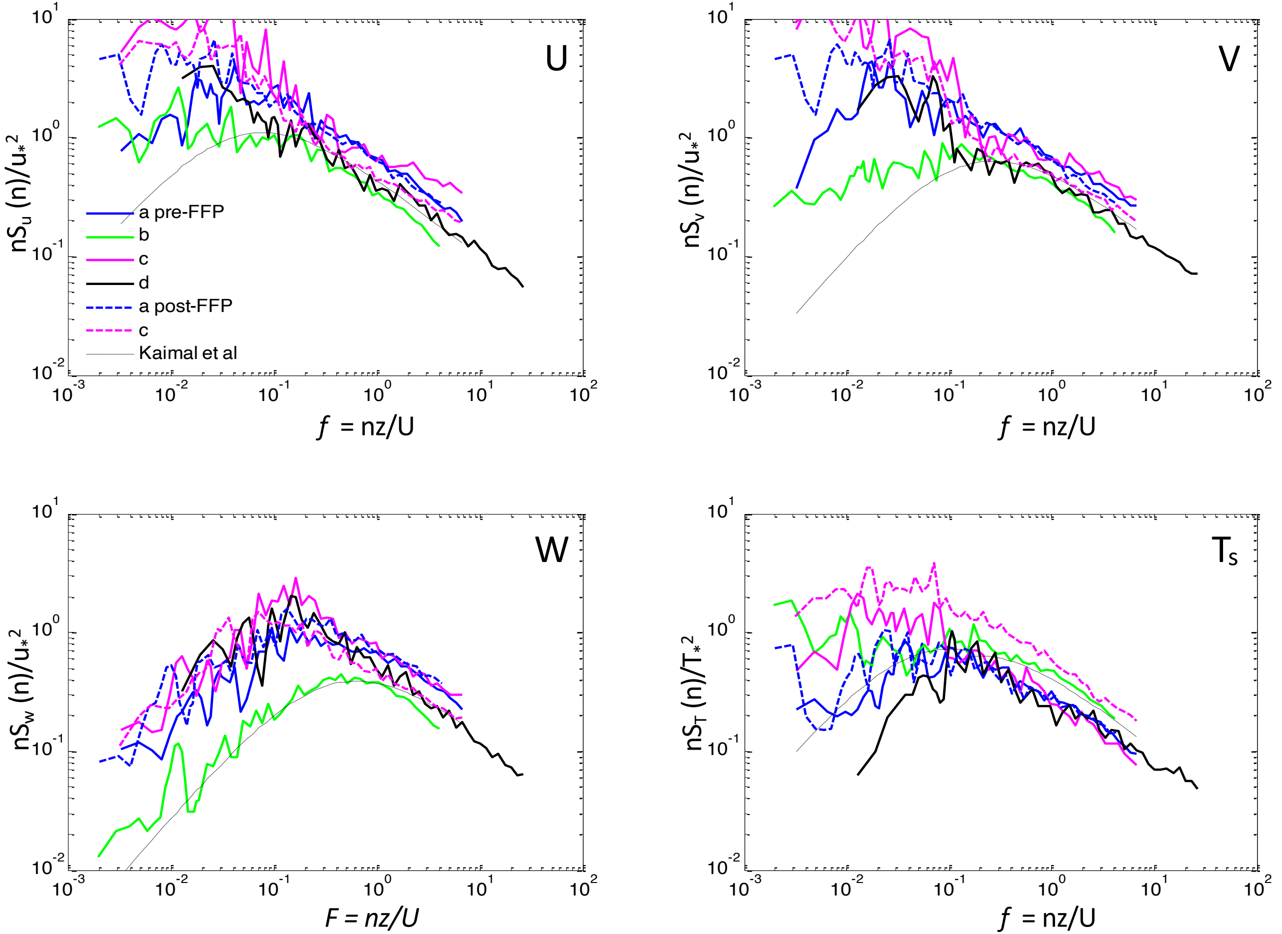




Multiple Experiments Under Various Conditions

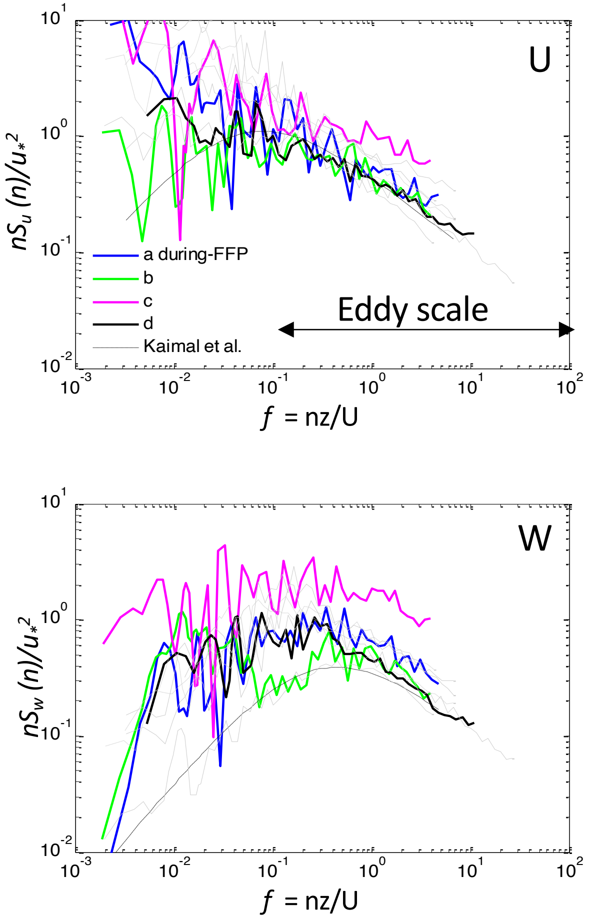
Normalized Turbulence Spectra: No Fire

(Seto et al. 2013, *Ag. Forest Met.*)



Normalized Turbulence Spectra: During Fire

Seto, et al.(2013)



Increase in velocity spectra at higher frequencies due to **shedding of small-scale eddies from fire front.**

TKE budget during grassfire

$$\frac{\partial \bar{e}}{\partial t} + U_j \frac{\partial \bar{e}}{\partial x_j} = \delta_{i3} \frac{g}{T_\mathrm{m}} \overline{u_i' T'} - \overline{u_i' u_j'} \frac{\partial U_i}{\partial x_j} - \frac{\partial \overline{u_j' e}}{\partial x_j} - \frac{1}{\rho} \frac{\partial \overline{u_j' p'}}{\partial x_j} - \varepsilon,$$

Desai et al. (2023)

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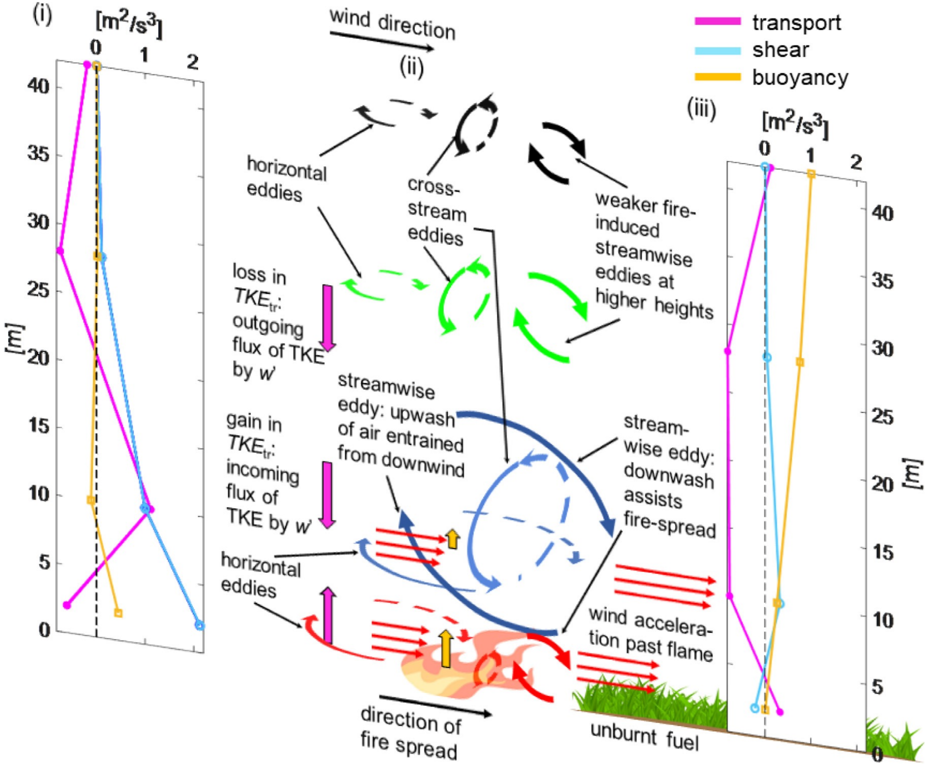
Features of turbulence during wildland fires in forested and grassland environments

Ajinkya Desai[a,*,1], Warren E. Heilman[b,2], Nicholas S. Skowronski[c,3], Kenneth L. Clark[d,4], Michael R. Gallagher[d,5], Craig B. Clements[e,6], Tirtha Banerjee[a,7]



- *both cross-stream and streamwise eddies strengthen with height before attaining a maximum (in this case, at the 10 m height) and starting to weaken with height.*
- *The strengthening of cross-stream eddies is important in the context of recent laboratory-scale experiments that suggested that cross-stream eddies advect hot gases forward onto unburnt fuel (Finney et al., 2015).*
- *Strong cross-stream eddies seen here could similarly participate in fire spread in the grassland environment and the height at which these eddies are the strongest provides the associated vertical length scale*
- *Furthermore, we infer that the downwash from strong streamwise eddies of this scale ($u'w' < 0$) also participates in the fire spread by pushing hot gases onto the unburnt fuel $w' < 0$ and $u' > 0$).*
- *These results are similar to initial hypotheses of Clements et al. (2007 which suggested that vortices generated from the entrained air push hot gases outward away from the flame. The near-surface wind also seems to accelerate past the flame: also an observation that was observed by Clements et al. (2007).*

What about plume scale?

RaDFIRE: Rapid Deployments to Wildfires Experiment

Camp Fire: Paradise, California, 9 November 2018

Halo Photonics Scanning Doppler Lidar

Measurements

- Aerosol backscatter
- Radial velocity

Scanning capability

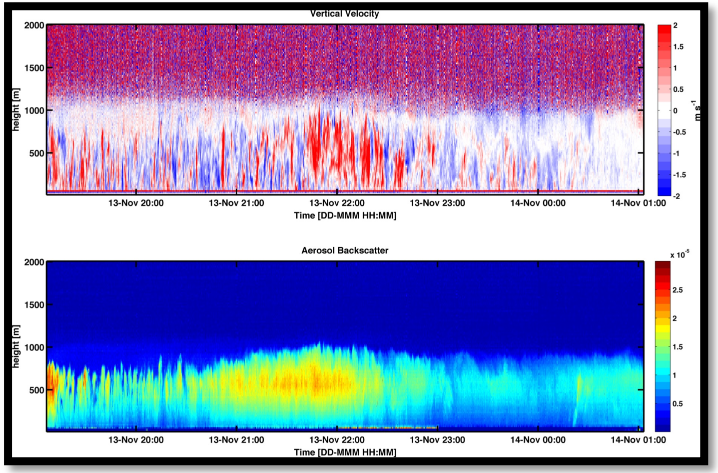
- 360° azimuth
- 180° elevation
- 9.6 kilometer range
- 18 meter resolution

CBL depth

Wind Profiles (DBS)

Solid State Drive

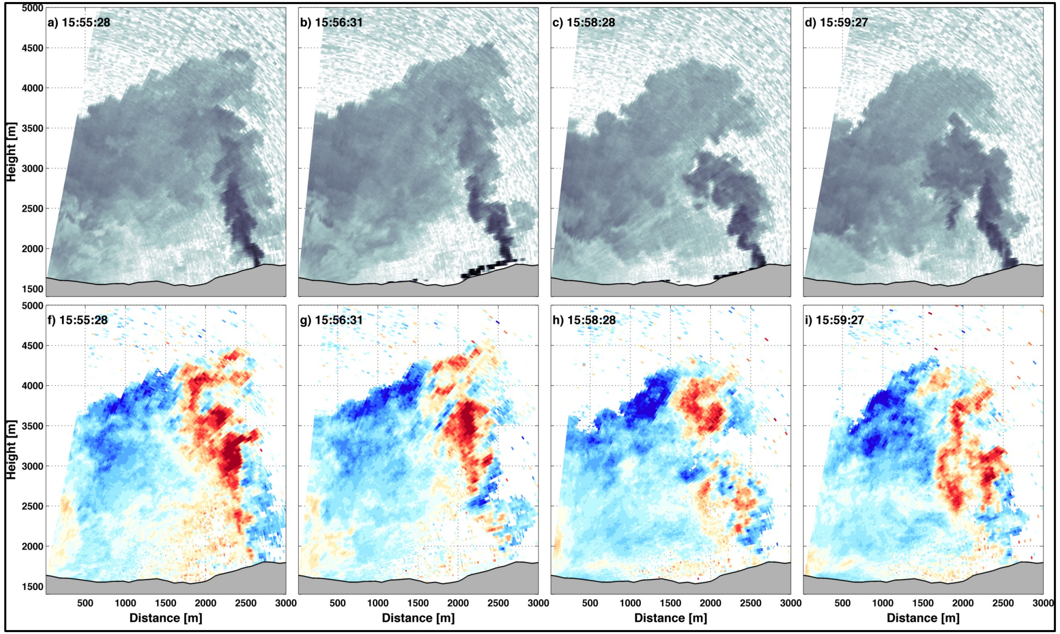
- Mobile operations

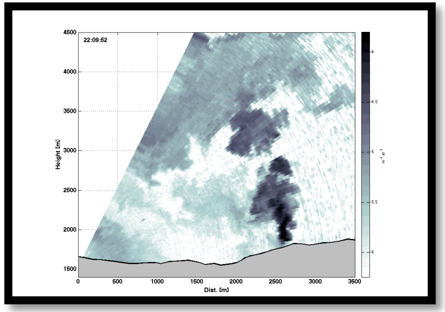


Observed structures associated with ordinary plume in cross wind

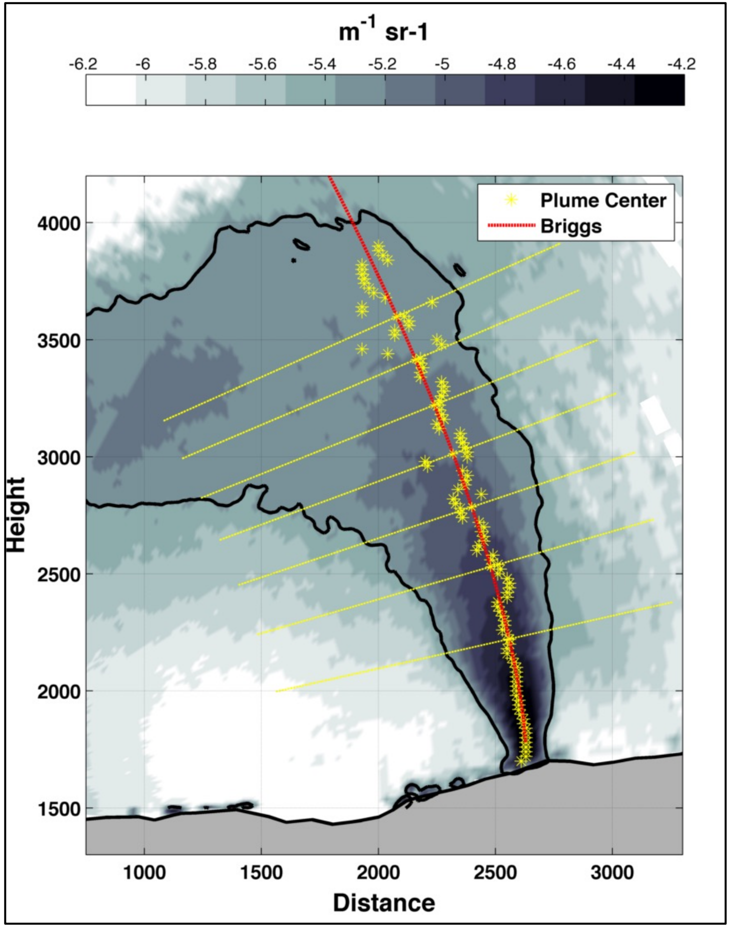
- Highly resolved plume observations– Smoke Backscatter (top) and Radial Velocity (Bottom)
- More than 1 hour of plume data with a slow moving fire in heavy fuels

Lareau and Clements (2017)

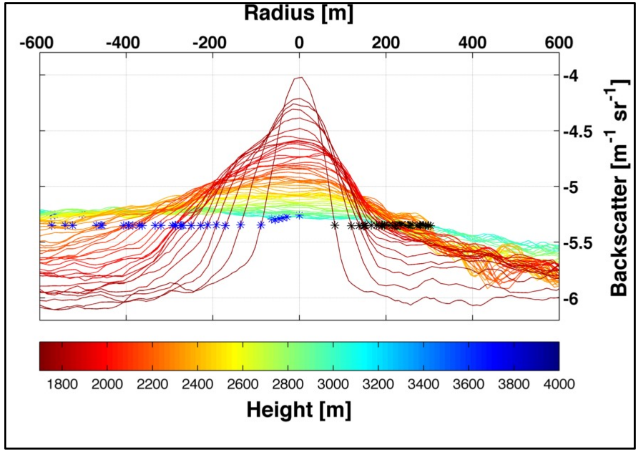




Mean Smoke Backscatter



Plume Cross Sections



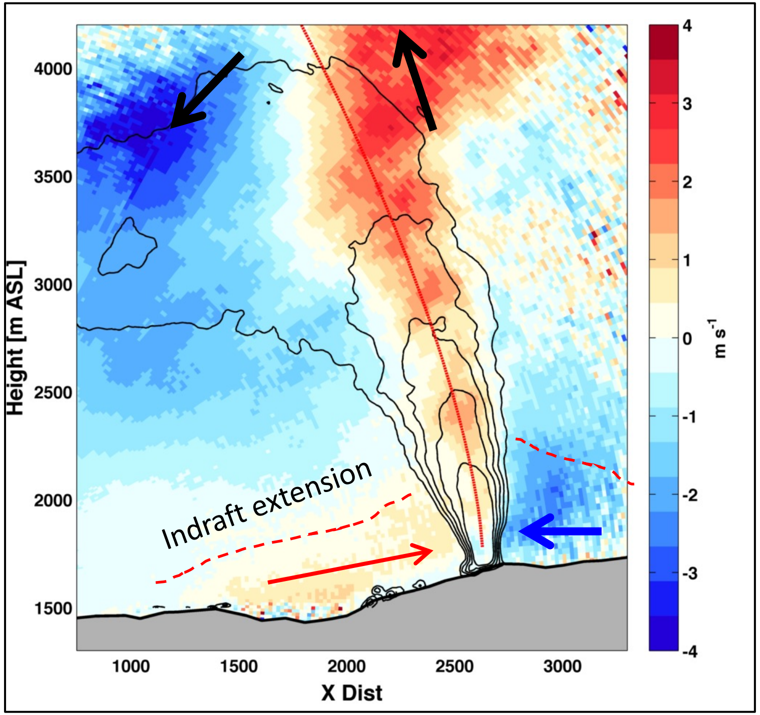
Mean Plume Structure:

- Plume in a cross wind ($u=3\ m\ s^{-1}$)
- Neutral stratification (up to 3500 m)
- Agrees with Briggs Plume rise:

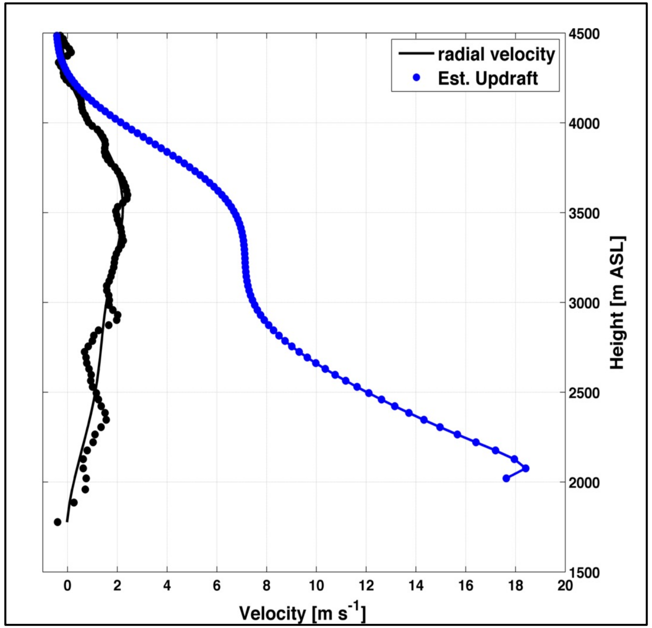
- Plume cross sections are approx. Gaussian
- Amplitude decays with height

Lareau and Clements (2017)

Mean Radial Velocity



Estimated Updraft



Mean Radial Velocity:

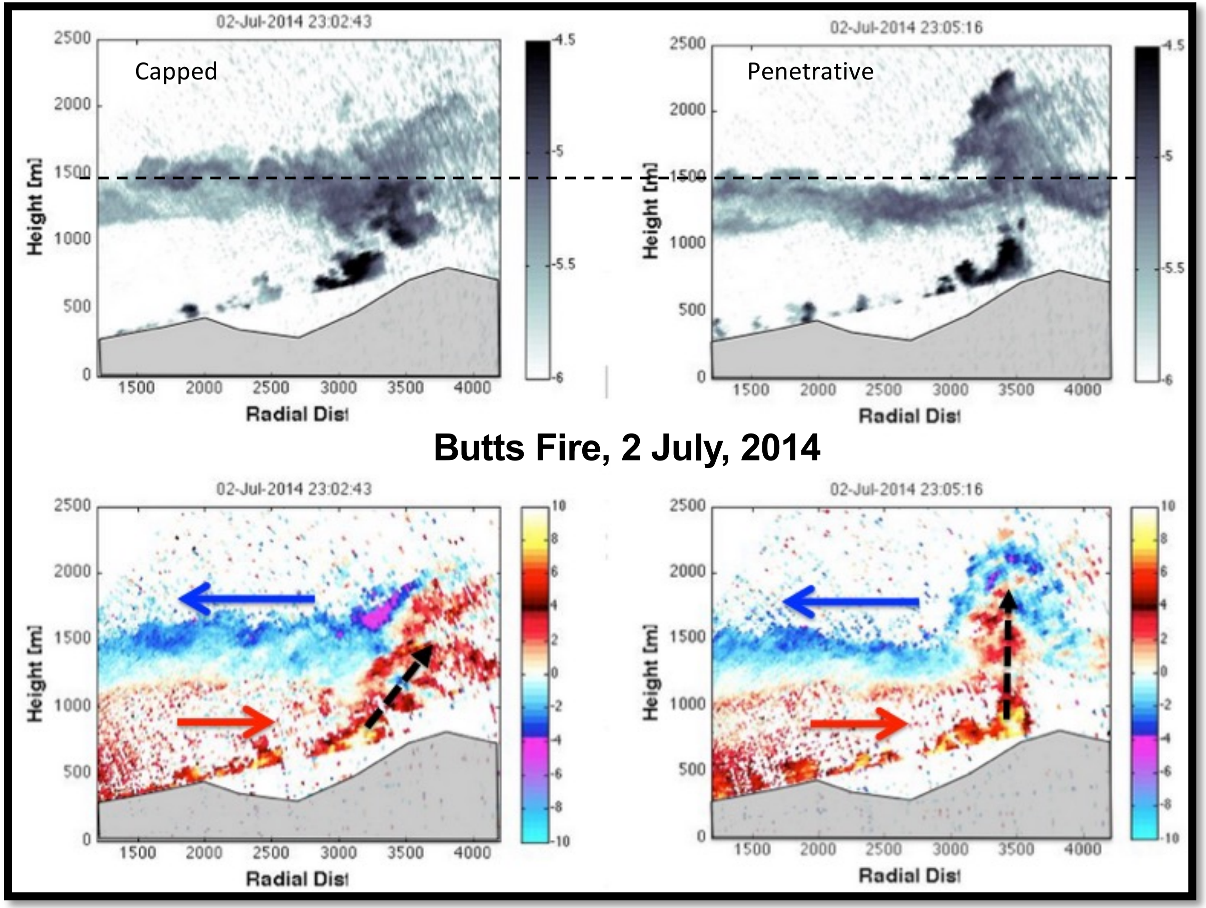
- Convergent flow into the base of the plume
- Overshooting tops (bright reds aloft)
- Compensating subsidence (dark blues aloft)

Radial Velocity and Updrafts:

- The radial velocity along the centerline is extracted (black line)
- Assuming the flow is along the center line the updraft strength is estimated (blue line)

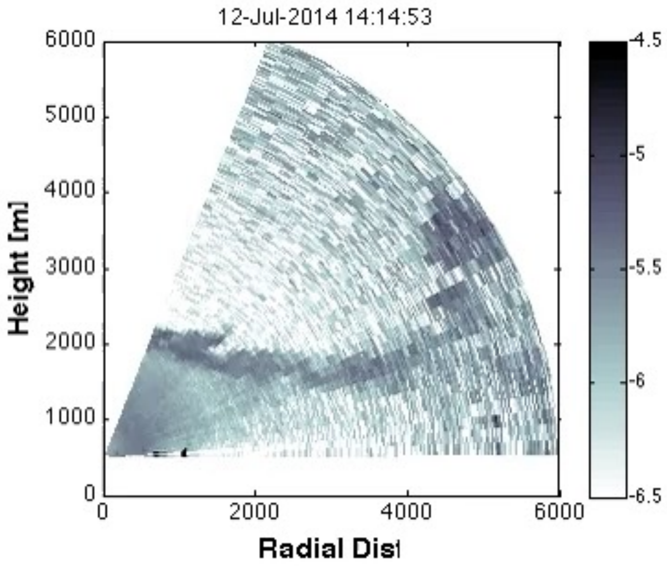
Lareau and Clements (2017)

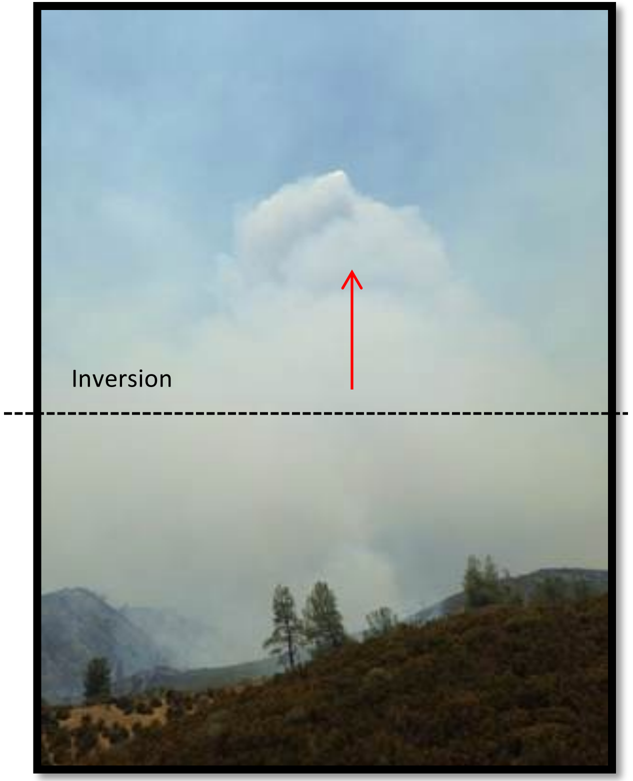
Inversion Layers and Smoke Plumes



Inversion Layers and Smoke Plumes

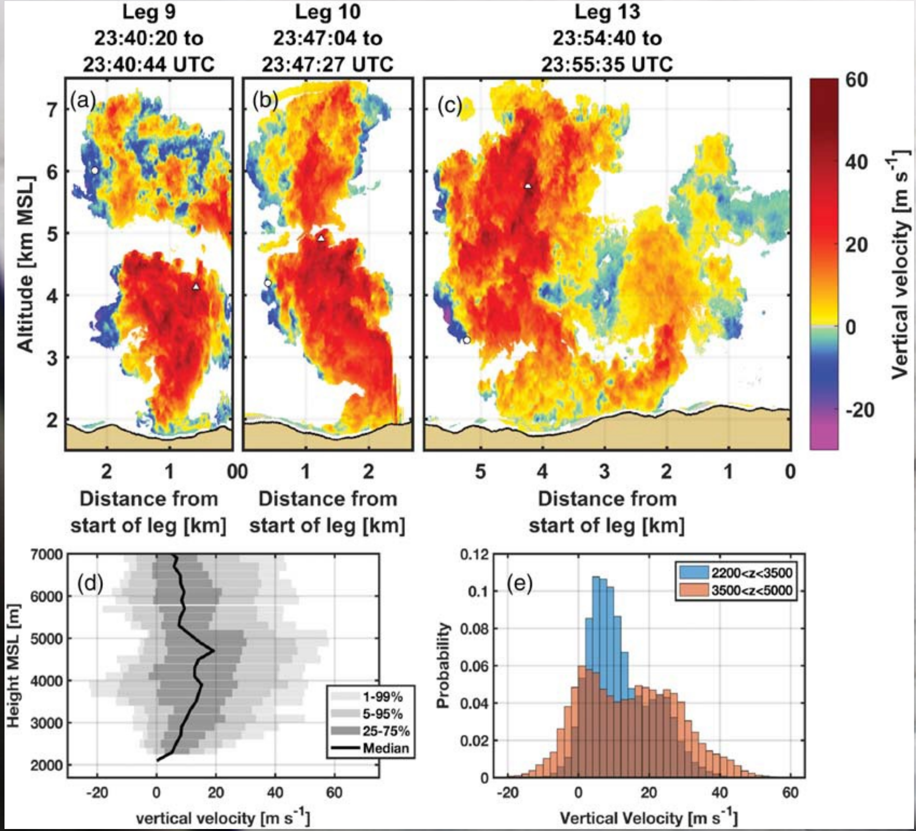
Range Height Indicator (RHI)





Bully Fire

Measuring Large PyroCb/Cu with Airborne Doppler Radar



- **Wyoming Cloud Radar (WCR)**
  - 95-GHz dual-Doppler radar
  - 15 m range gates
  - Corrected for aircraft motion (Haimov, 2013)
  - Up-down profiling mode

Rodriguez et al. (2020)

Geophysical Research Letters

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10.1029/2020GL089001

Special Section:
Fire in the Earth System

Extreme Pyroconvective Updrafts During a Megafire

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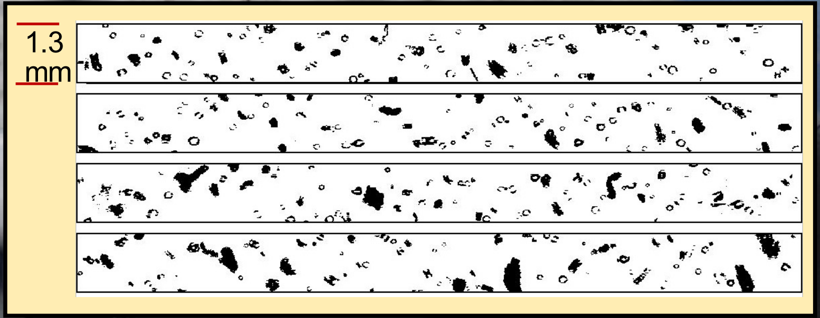
[1]Department of Meteorology and Climate Science, San José State University, San José, CA, USA, [2]National Weather Service, San Diego, CA, USA, [3]Department of Physics, University of Nevada, Reno, Reno, NV, USA, [4]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA

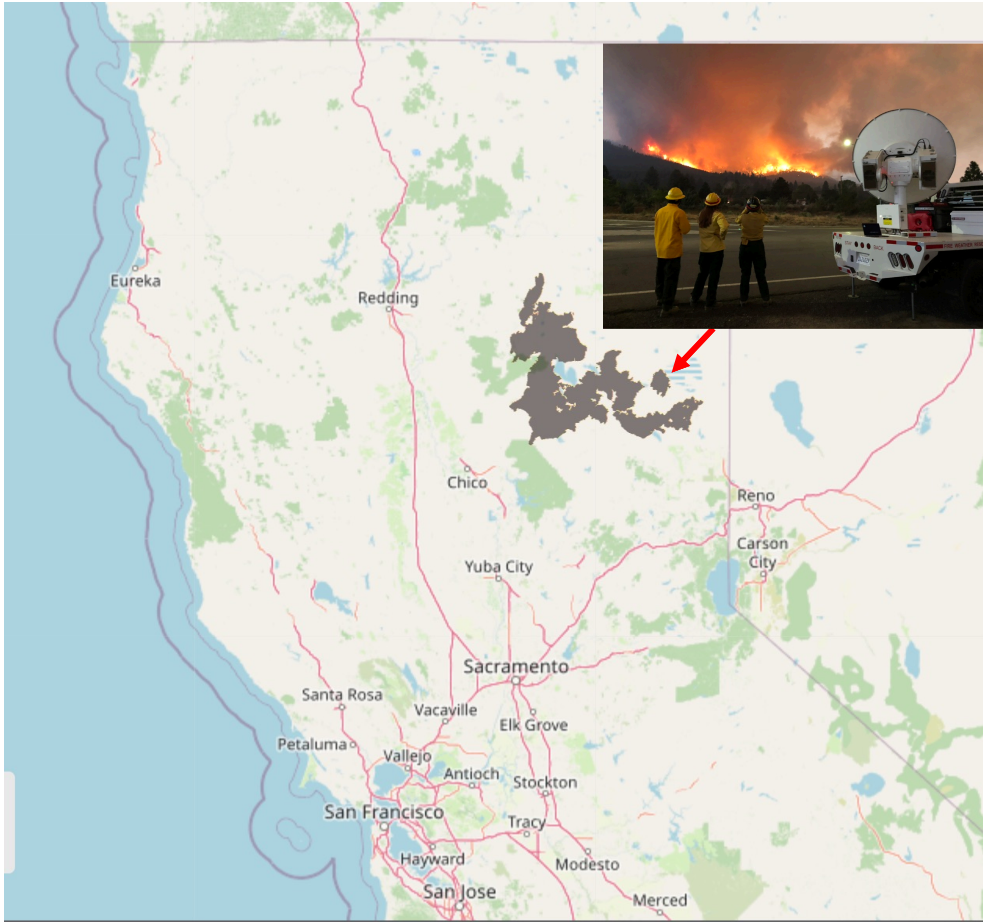
Very strong (~58 m/s), deep updrafts with strongest velocities observed well above ground level

Small “cloud droplets?”
Non-zero “pyrometeor” concentrations

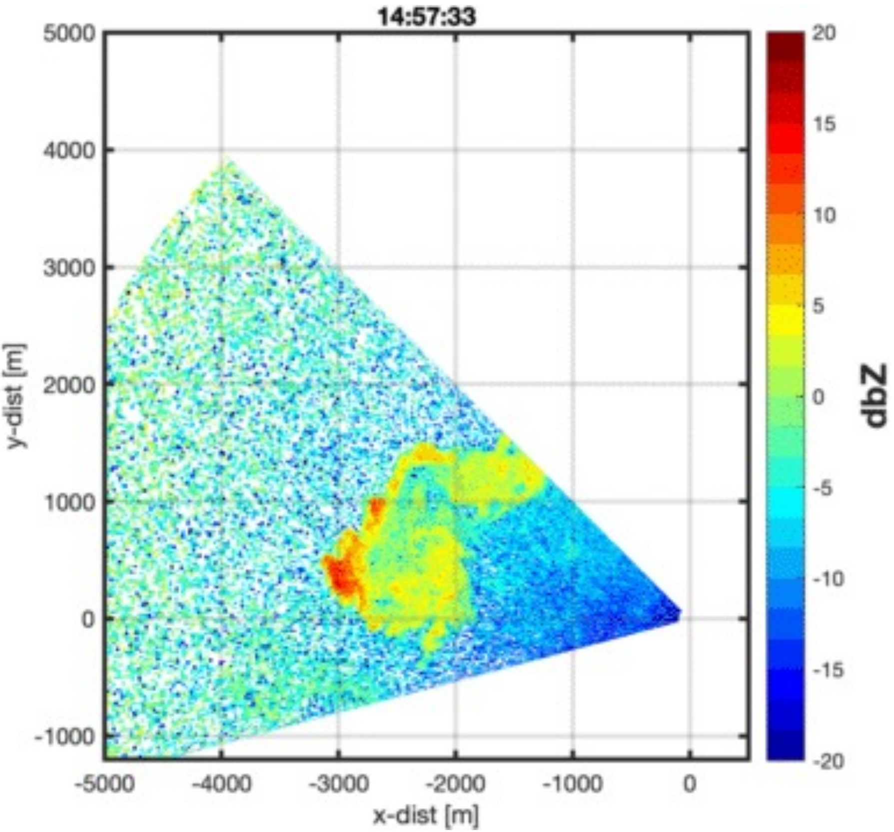


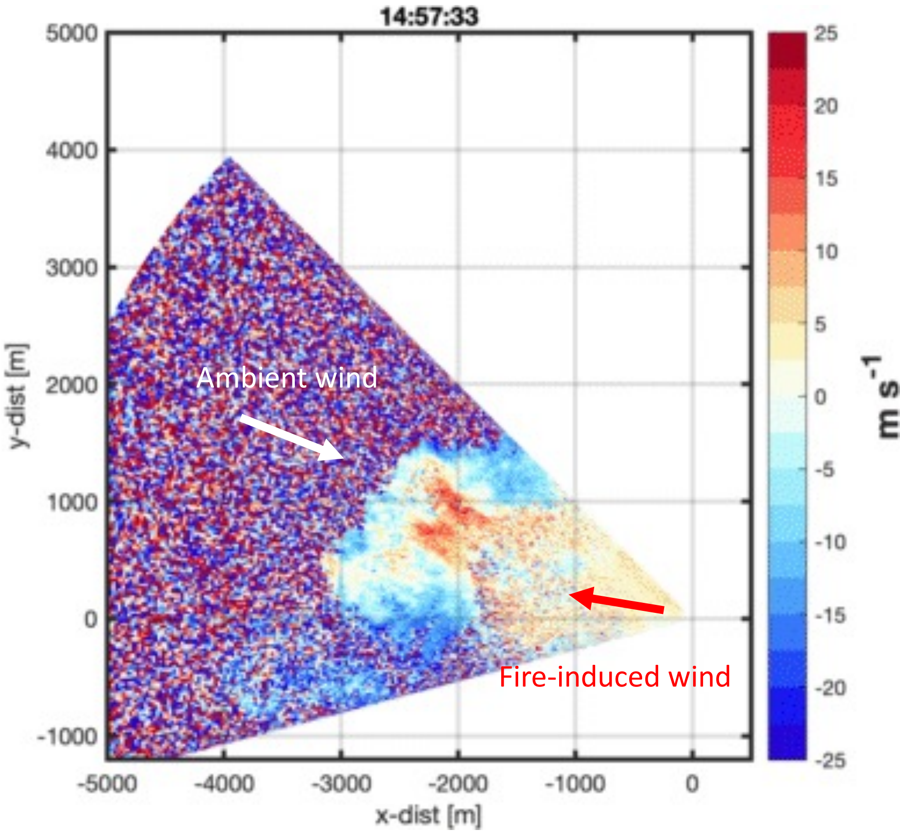
Dixie Fire: California's Largest Wildfire

- Started on July 13, 2021-October 25, 2021
- 3,898 km^2; 389,837 hectares

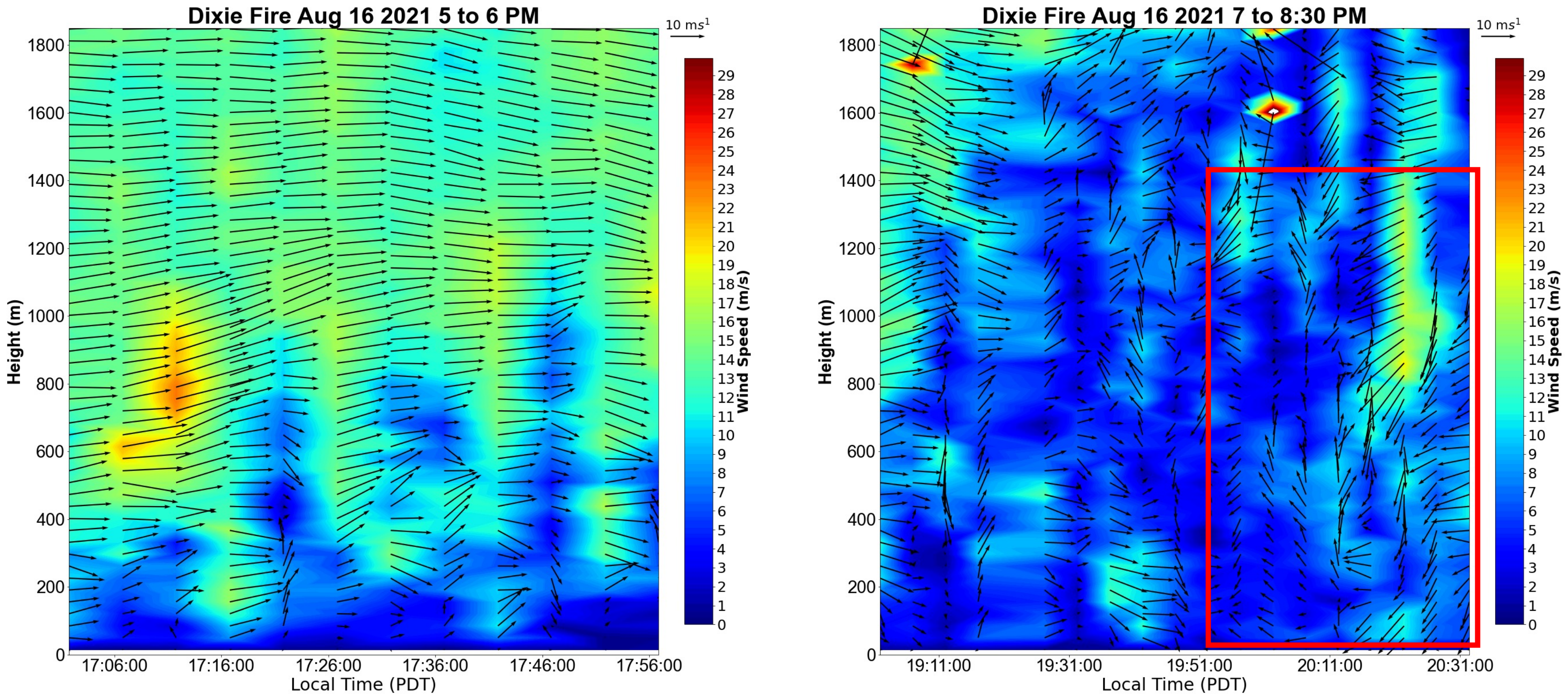


Dixie Fire: Lee-side counter rotating vortex pairs (CVPs)





Dixie Fire: Deep Fire Induced Wind Reversal



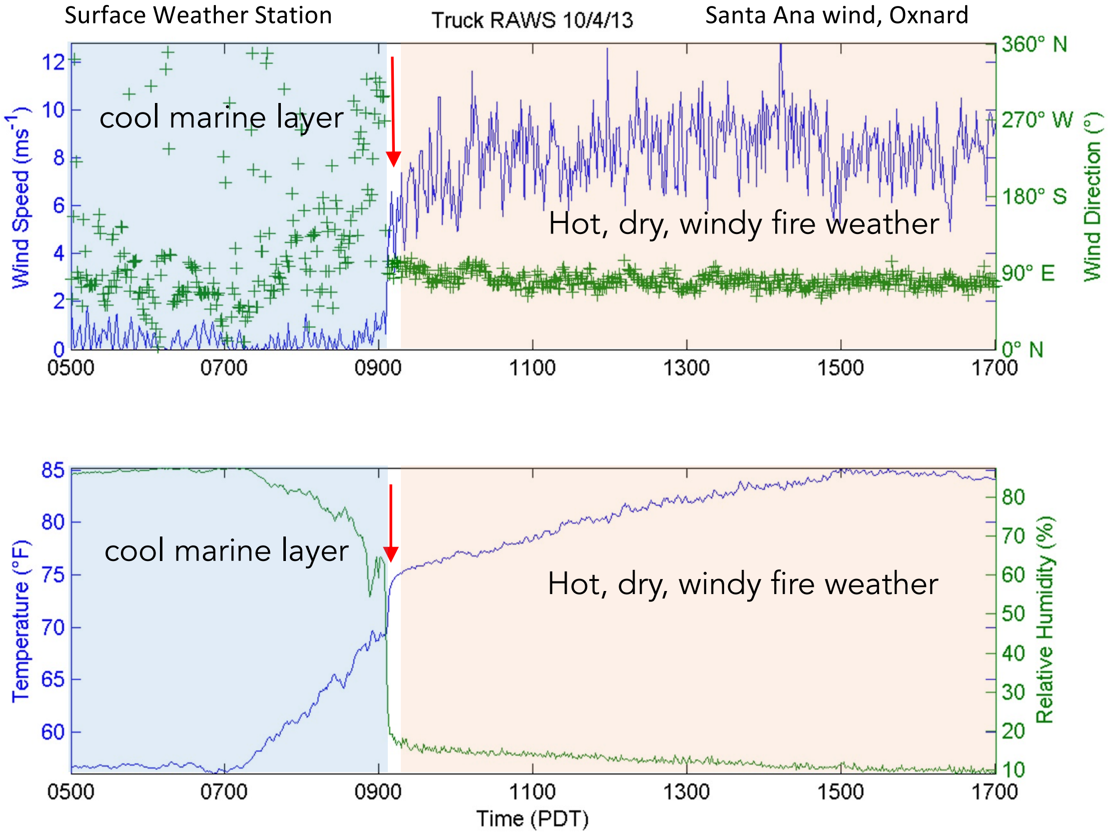
Extreme wildfire behavior associated with complex terrain

Collaborators: Neil Lareau (UNR), Adam Kochanski (SJSU), Marwan Katurji (U. Canterbury), Domingos Viegas (U. of Coimbra), Jason Sharples (UNSW)

Rapid Onset of Downslope Wind Events: impacts on surface meteorology

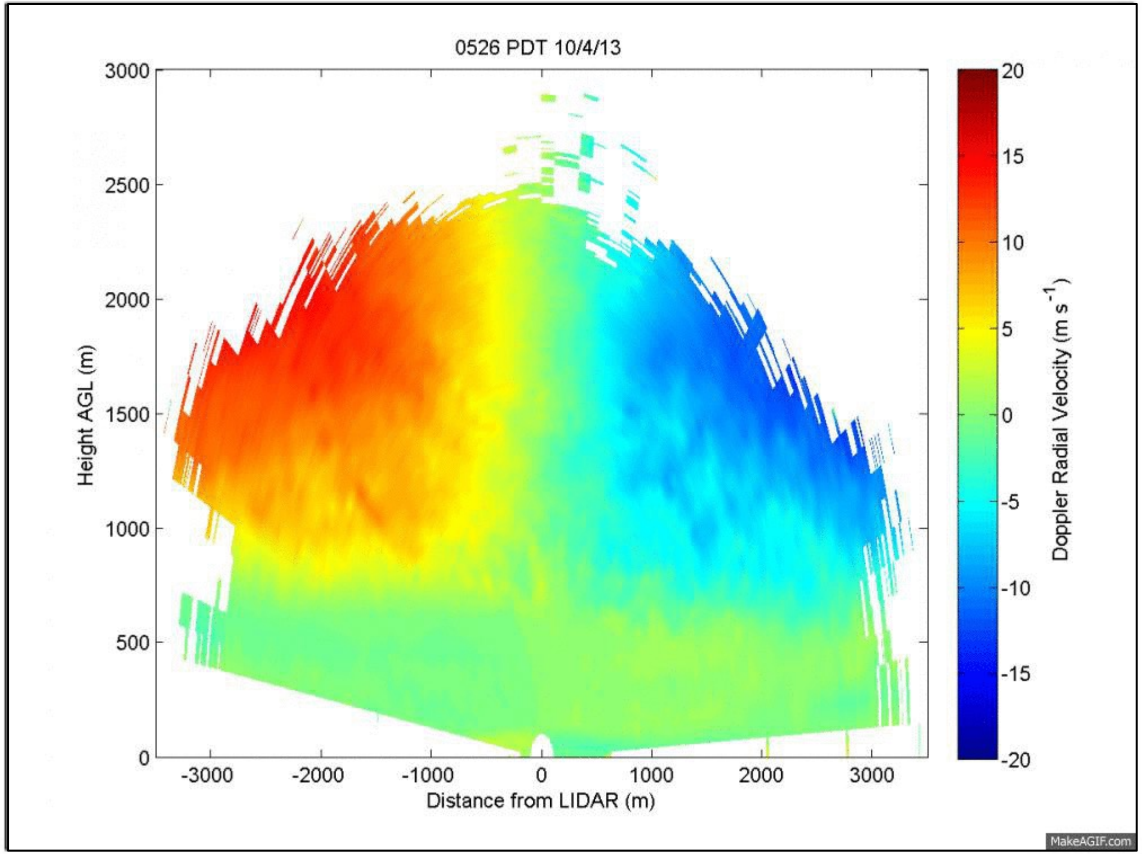
Transition from marine layer to dry Santa Ana wind environment.

Rapid changes in weather = rapid changes in fire behavior



Lidar RHI Scans: Santa Ana winds mixing down to surface

Radial Velocity- Oxnard, CA Oct 2013

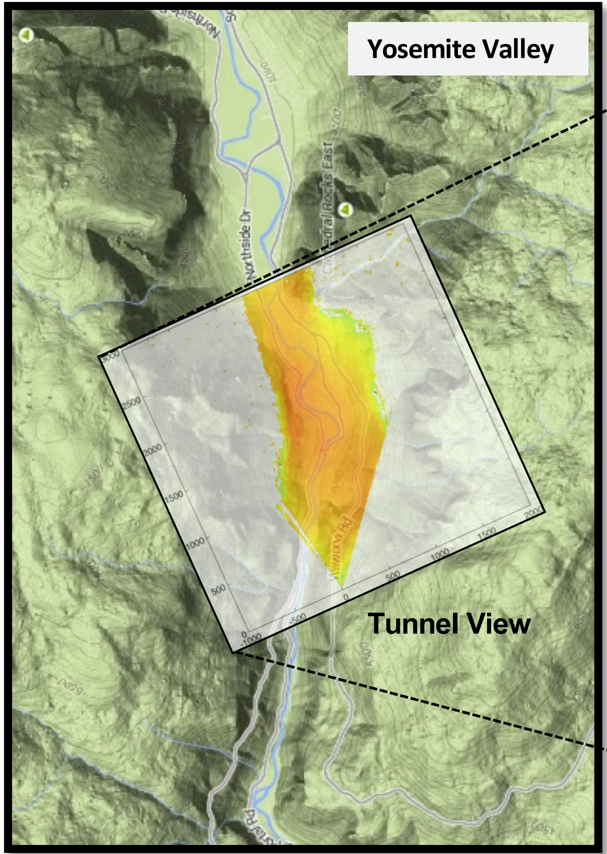


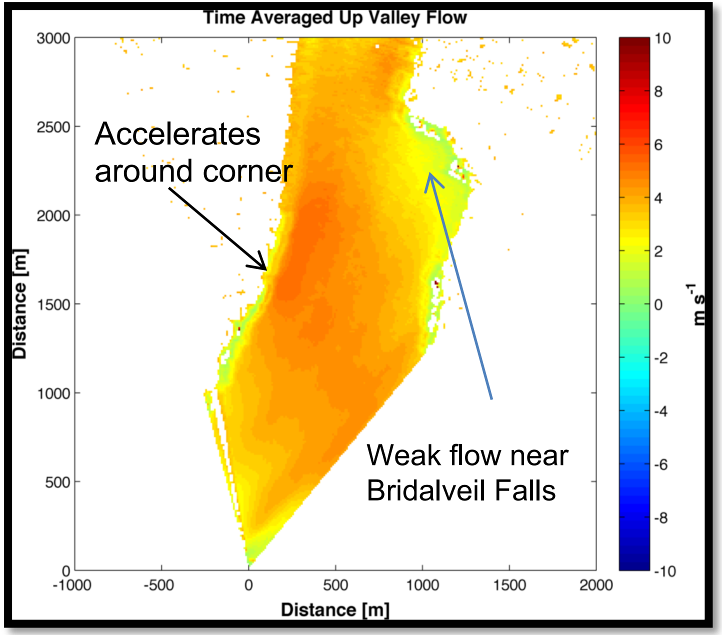
Blue shading = winds towards lidar

Red shading = winds away from lidar

Horizontal Variability of Along-Valley Winds

Afternoon Up-Valley Flow





Fire spread will vary based on both the turbulent and mean flows.

Expect higher ROS near canyon bends if fuels are homogeneous (which they never are).

Morning and evening transition periods can modify fire behavior.

The California Canyon Fire Experiment

24 October 2022

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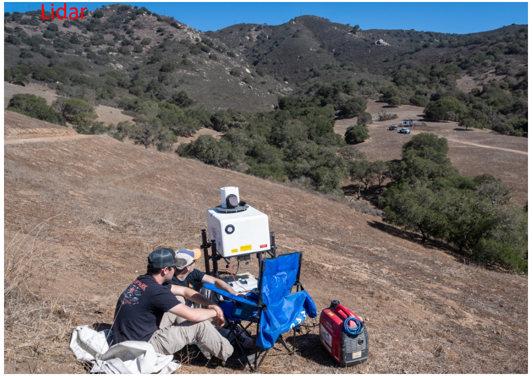
Some instruments and platforms

Fire Behavior Packages

Airborne IR imaging (SWIS)

Doppler Sodar

Doppler Lidar



Mobile Met Tower 32 m

Sonic Anemometers 10 m

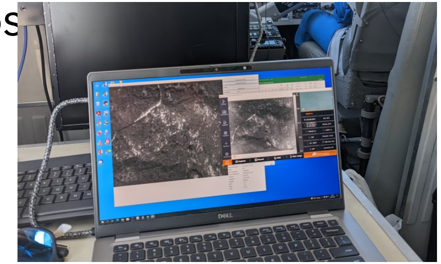
Drone- IR and video

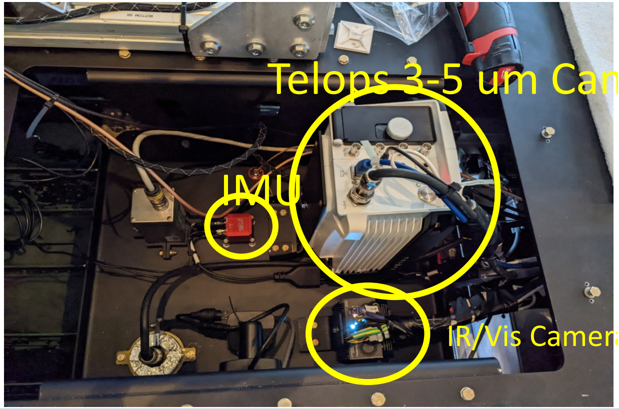
Sonic Anemometers 10 m

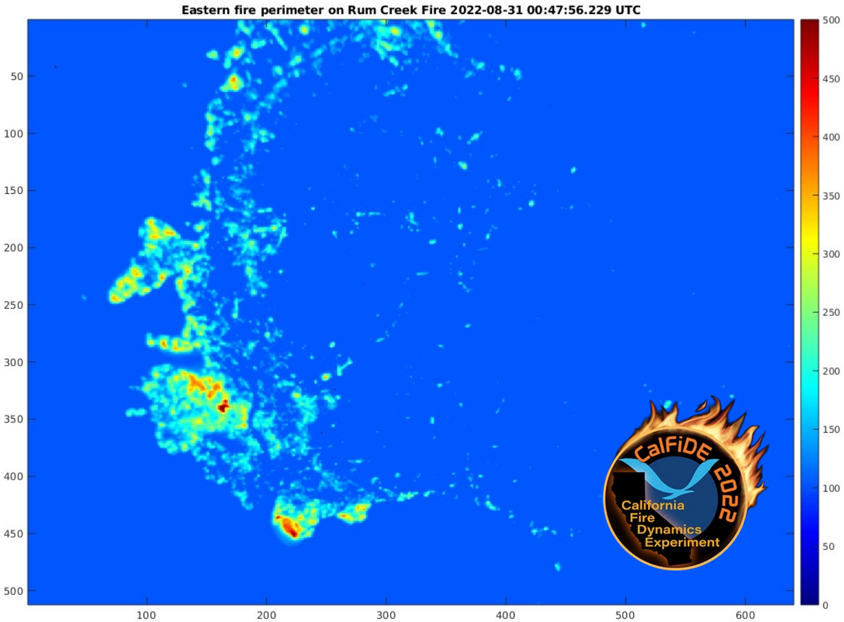
Ka Doppler radar

SJSU Wildfire Imaging System (SWIS)

- Custom designed system for real-time fire behavior monitoring.
- High-resolution infrared image system with custom software for fire behavior metrics.
- Does not saturate, provides high spatial and temporal obs







Summary

Observations from both small-scale experiments and large wildfires provide critical data on atmosphere coupling processes.

Key points from the small scale:

- Fire Front Passage characterized by increases in surface winds and turbulence, wind reversal, pressure decrease.
- Pressure perturbations form at and down wind of fire front––accelerating flow into the fire front.
- Increase in velocity spectra at higher frequencies due to shedding of small-scale eddies from fire front.
- Normalized velocity spectra during FFP collapse reasonably well into a narrow band, and overall slope was conserved at higher frequencies.
- Turbulence dominated by buoyancy production vs shear production even under moderate winds.

*See paper by Katurji et al. on atmospheric turbulence Monday 345-400PM Room 4

Summary

Plume scale

- Doppler lidars and radars provide highly resolved measurements of plume structures at multiple scales.
- Ordinary plumes can be approximated by Briggs and plume cross sections have gaussian distribution.
- Overturning of plumes can provide intermittent negative heat fluxes—may impact fire behavior at the smaller scale.
- Convergence flow and fire-induced winds can extend out to kilometers from plume base.
- Radar observations show pyrometeor cores or "high-reflectivity cores" transporting larger debris through the extent of the plume.
- Extreme updrafts of 60 m s^{-1} have been observed well above the surface in pyroCb.

Fire-Atmosphere Interactions at multiple scales

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Thank you!

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WIRC Wildfire Interdisciplinary Research Center