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The California Fire Dynamics Experiment (CalFiDE): Developing Validation Data Sets for Coupled Fire-Atmosphere Simulations

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Abstract

The California Fire Dynamics Experiment (CalFiDE) is a 6-week study of wildfire behavior and its response to spatially and temporally evolving wind fields in California, USA. It is the result of a partnership between the Chemical Sciences Laboratory (CSL) at the National Oceanic and Atmospheric Administration (NOAA), the Wildfire Interdisciplinary Research Center (WIRC) at San Jose State University (SJSU) and University of Nevada, Reno. A Twin Otter aircraft will be instrumented and flown over landscape-scale wildfires in California between August 14 and September 30, 2022. Onboard instrumentation includes (i) a scanning Doppler lidar system capable of measuring vertical profiles of 3D wind speed and turbulence, (ii) a multispectral infrared imaging system designed to remotely sense fire behavior, (iii) NightFox fire radiative power sensors (iv) AIMMS probe to measure flight-level winds, temperature, and water vapor content, and (v) Chemistry instruments to sample flight level NOX , NOY, O3, CO and GHG. Airborne measurements will be complemented with ground-based mobile scanning radars and lidars, which will be positioned around the fire to characterize the spatial structure and internal dynamics of the smoke plume. This combination of sensors will provide a unique opportunity to characterize landscape-scale wildfire behavior, fire weather and fire atmospheric chemistry in a synchronized manner. We expect that the datasets resulting from this experiment will have a broad applicability in fundamental fire dynamics studies, fire model validation exercises and the calibration of spaceborne remote sensing fire observations.

1. Introduction

Rigorous observation of fire behavior and fire meteorology during landscape-scale wildfires is essential to develop and validate wildfire models. Validation of coupled fire-atmosphere models, for example, poses unique data challenges that have so far limited rigorous model assessment. In order to validate coupled fire models, observational data must be comprehensive enough to validate all of the model components. For fire spread focused implementations, coupled fire models involve an atmospheric component, a fuel moisture component, and a fire spread component, while air quality applications require additional emission, aerosol and chemical transport modules. As these model components are interlinked, an error in one module can impact the final fire simulation results beyond the specific physical processes modeled by that module. For example, model inaccuracies in the rate of spread may be a result of the deficiencies of the fire spread component itself, but also due to the model's inability to resolve ambient weather conditions, or limitations in representing the local fire-induced circulation. An example of the fire-induced circulation simulated by a coupled fire-atmosphere model (WRF-SFIRE) is presented in Figure 1.

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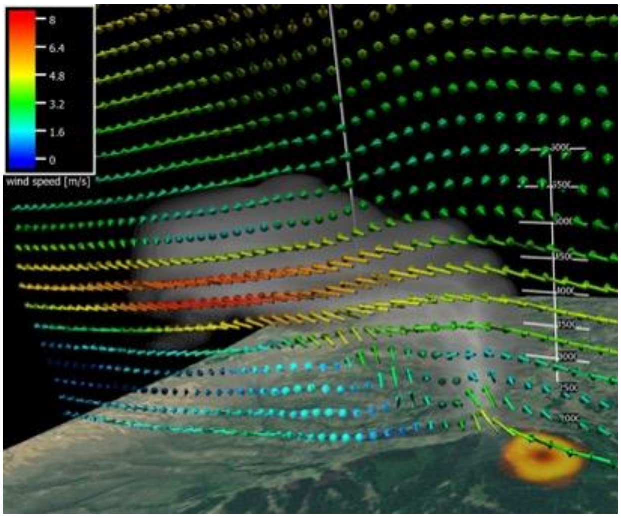

Figure 1. Example of a fire-induced circulation simulated by WRF-SFIRE, a coupled fire-atmosphere model, for Langdon Burn in Utah National Forest, November 7th 2019.

At present, no suitable datasets exist for validating and improving current and future coupled fire-atmosphere models that predict the spread and impact of landscape-scale wildfires (i.e., 1000s of acres). While validation datasets exist for small-scale fires (e.g., Craig B Clements et al. 2007; C B Clements et al. 2014; Craig B. Clements et al. 2019; Ottmar et al. 2016), the physics of landscape-scale fires are different, with processes such as long-range spotting, strong fire-induced winds, large vortex formation, and pyrocumulonimbus (pyroCB) development impacting fire processes.

CalFiDE has been designed to address this problem by integrating airborne and terrestrial remote sensing systems to simultaneously characterize fire behavior, plume dynamics and local circulations near the fireline. Data will be acquired using a rapid deployment strategy during active fires with a combination of airborne infrared (IR) camera systems, airborne Doppler lidar, truck-mounted scanning Doppler radar, and a suite of truck/trailer mounted scanning Doppler lidars. These observations will resolve process-level details of the fire (rate of spread, fire radiative power, etc.), fire-induced winds, plume rise dynamics, and pyroCb development. This sampling approach will provide the necessary data to validate model forecasts and diagnose deficiencies in model physics.

2. Sensor description

The primary objective of CalFiDE is the spatially and temporally resolved observation of fire dynamics and micrometeorology in the fire environment. Consequently, the main sensing packages designed to be deployed during this experiment include (a) an airborne Doppler lidar to characterize the wind field around the fire and plume, (b) an infrared multispectral imaging system to track fire progression and measure fire behavior, and (c) a set of ground-based mobile radar and lidar sensors to characterize vertical winds, smoke plume dynamics and boundary layer evolution. In addition, a number of physical and chemistry sensors will be installed on the aircraft to make in-situ measurements of flight-level thermodynamic conditions as well as air chemical composition. Table 1 summarizes CalFiDE’s sensing capabilities, whereas the rest of this section provides additional detail on the main instrumentation.

Table 1: Summary of CalFiDE's sensing capabilities.

Sensor	**Deployment strategy**	**Measuring capabilities**	**Resulting data products**
Airborne Doppler Lidar	Airborne	Partial hemispheric scans of wind speed and direction	Horizontal wind profiles and vertical motion in the fire area
Visible camera	Airborne	3-band color images	Contextual visual information about the fire scene
Mid-wave IR camera	Airborne	Broad-band irradiance in the midwave infrared range	Fire Radiative Power, Brightness Temperature, identification of flaming vs. smoldering areas
Long-wave IR camera	Airborne	Broad-band irradiance in the longwave infrared range	Fire geometry, fire line location, fire rate of spread, identification of flaming vs. smoldering areas
NightFox	Airborne	Scanning radiometers @ 1.6µm & 4µm (± 30°)	Spatially resolved Fire Radiative Power
NOxCaRD & PICARRO	Airborne	NO$_x$, NO$_Y$, O$_3$, CO and GHG	Ozone Photochemistry and Fire Impacted Urban O$_3$
Ka-Band Polarimetric Doppler Radar	Ground-based, mobile	Radar reflectivity, radial velocity, and polarization	Fine-scale kinematics and microphysical properties of active wildfire smoke plumes
Scanning Doppler Lidars	Ground-based, mobile	Lidar backscatter intensity and radial velocity	Smoke plume dynamics, kinematics, horizontal wind fields and turbulent properties

2.1. Airborne Doppler Lidar

Dynamics of the plume and wind fields surrounding the fires will be measured using a Doppler lidar installed on board the NOAA Twin Otter aircraft. Combined with a partial hemispheric scanner that allows for measurements both below and above the aircraft, the lidar will provide profiles of the horizontal wind field, vertical motions, and aerosol backscatter intensity throughout the boundary layer. Figure 2 shows the morphology (a) and vertical motions (b) of a fire plume emanating from a fire shown as a red hot spot in the ground track. The horizontal wind profile, shown as colored arrows pointing in the direction of flow in the foreground, indicates 5 m/s flow with a strong directional shear layer at 1000m. In Figure 2b upward motions in the plume are shown in warm colors.

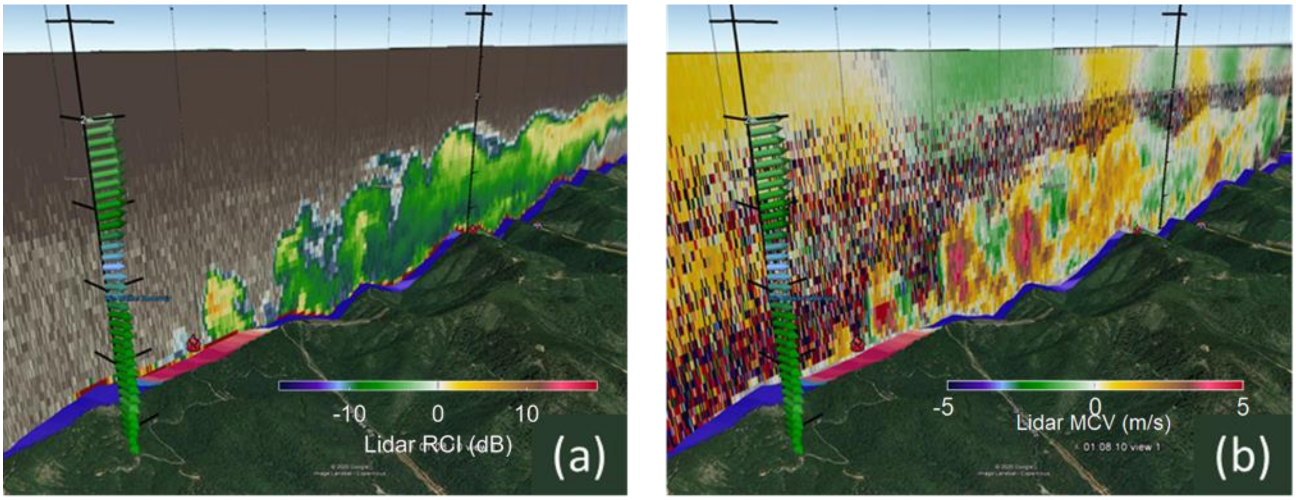

Figure 2: Doppler lidar data from a wildland fire during a previous NOAA field campaign on the Twin Otter. The red area at the surface indicates the fire area. Arrows on the left axis of each figure indicate horizontal wind speed and direction. The colored fields indicate; (a) aerosol backscatter intensity, and (b) vertical velocity.

2.2. Airborne Infrared Imaging System

Fire behavior will be monitored using a combination of optical sensors operating in the visible, medium-infrared (3.9 µm), and thermal-infrared (8-14 µm) spectral ranges. This selection of bands will allow measuring fire location, fireline geometry, rate of spread, and fire radiative power with a spatial resolution of about 3m for a nominal flight altitude of 11,000 ft. The across-track swath sampled by the camera system will be ~2 km. All optical sensors will be mechanically coupled to an inertial navigation system (INS) which will provide geolocation and attitude information for image direct georeferencing. Raw inertial navigation measurements taken in real time will be corrected after the mission using Post-Processing Kinematics (PPK). Furthermore, direct georeferencing outcomes will be refined using image processing algorithms like those described in (Valero, Jimenez, et al. 2018; Valero et al. 2021). The resulting georeferenced imagery will be analyzed using the methodology developed by (Valero, Rios, et al. 2018) and it will also be used for the identification of spot fires. Figure 3 shows an example of observations collected using this methodology in a previous small-scale experiment.

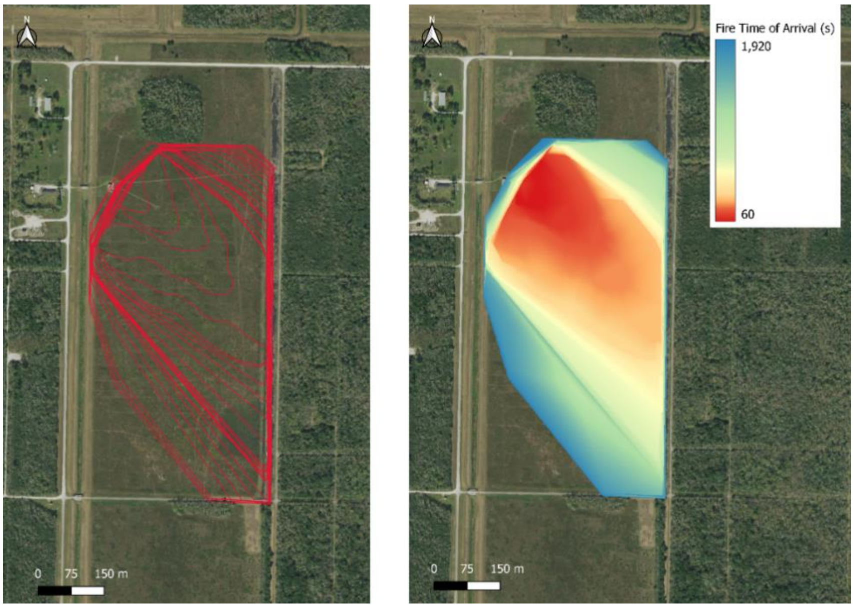

Figure 3. Fire progression during the FireFlux II experiment (Clements et al., 2019) derived from airborne IR imagery. Left: fire perimeter at 60-s intervals. Right: fire time of arrival at every location in the burn unit, relative to the time of ignition. Base image provided by the USDA National Agriculture Imagery Program.

2.3. Ground-Based Mobile Radar

Time-and-space resolved observations of wildfire plume structure will be generated with SJSU’s truck-mounted scanning Ka-band (35 GHz, 8-mm) fully polarimetric Doppler radar (SKAR). These data will quantify plume volume, plume injection height, and pyroCu/Cb initiation. SKAR has a narrow beam width (0.33°), 15 km range, and range gate resolution of up to 5 m, and scans the full upper hemisphere in ~ 2 minutes. The SKAR’s capabilities in probing wildfire plumes is well-established (Aydell and Clements 2021). Figure 4 shows SJSU’s truck mounted Doppler radar (a) and Doppler lidar (b).

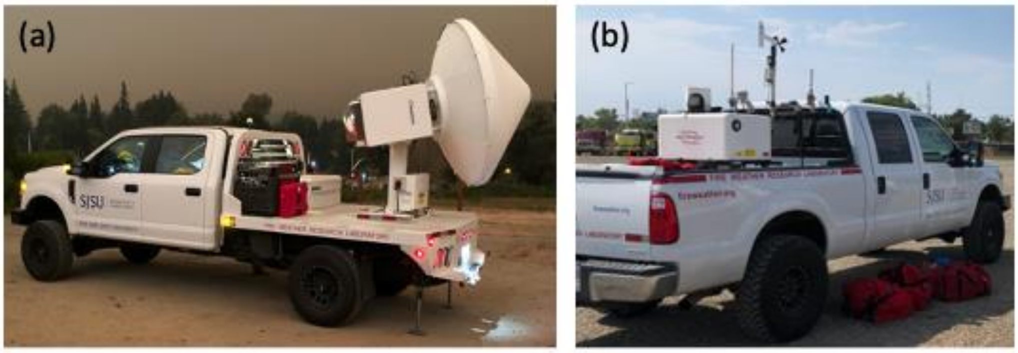

Figure 4. SJSU’s Doppler Ka-band radar (a) and Doppler lidar (b).

2.4. Ground-Based Mobile Lidars

Two scanning Doppler lidars (SJSU, UNR) will be deployed within 1-2 km of the fire front to characterize plume structures and dynamics and atmospheric vertical wind profiles and boundary layer evolution. These data are critical for understanding the coupling of fire and atmospheric processes that can drive rapid fire spread and intensification.

Additionally, a NOAA motion-stabilized truck-based lidar will measure convective boundary layer (CBL) depth, vertical velocity variance, and horizontal wind profiles proximal to the fire, but away from the fire front.

3. Experiment design

The project will be headquartered in San Jose, CA between August 14 and September 30, 2022. Ground-based instruments will be staged on the SJSU campus. The research aircraft will be staged at the San Jose International Airport (KSJC), or other ad-hoc flight bases as necessary. Instruments and crews will deploy to wildfires on a day-to-day basis within intensive observing periods (IOPs).

IOPs will be declared one to three days in advance. Five IOPs are planned, each up to 3 days, yielding a total of 15 research days for the ground assets. Observations will typically occur from 12 AM to 8 PM (local time) in order to capture peak fire behavior. The aircraft will make two afternoon flights, separated by refueling. Operations meetings will be held each morning and evening to examine weather and fire conditions, research objectives, and instrument sitting.

Potential “blow-up” fires will be identified through a combined examination of weather, fire and plume development, fuels, topography, and simulated fire growth. UNR and SJSU forecasters will provide daily weather briefings to monitor conditions conducive for “blow up” fires. Satellite IR and NIROPS fire perimeters will be used to track day-to-day fire growth. NEXRAD radar, visible satellite, and webcam networks will be used to track plume development. Maps of topography, fuel type, fuel load, and fire history will be used to estimate growth potential for active fires. Finally, once a fire of interest is identified, an existing “point-and-click” web interface for the WRF-SFIRE simulator (WRFXPY) will be used to predict the expected mesoscale weather evolution and fire growth for a 54-hour window.

Aircraft flight paths will typically follow a “lawn mower” crosswind pattern just upwind of the plume core. An emphasis will be placed on keeping the head fire within the 2 km scan swath of the IR instrumentation. Flight altitudes will be confined between the Temporary Flight Restriction (TFR, ~10,000 ft) and 16,000 ft, which is the flight ceiling. Truck-mounted radars and lidars will deploy to safe locations within 5 km of the head fire. Where possible the locations will be distributed to provide view angles with >30° of separation to measure different components of the wind. Previous deployments have used scenic overlooks, rest stops, reservoirs, ski areas, helipads and airports, and open meadows as safe locations with good field of view.

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