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Introduction

A comprehensive field program collected fuel consumption, particulate and trace gas emissions, near-fire thermal-induced atmospheric transport properties, and smoke dispersion observations during a prescribed sub-canopy burn. Two research burns took place in The Nature's Conservancy's Calloway Forest, NC, in a long-leaf pine (*Pinus palustris* Mill.) plantation undergoing diversity restoration. Observation data were collected before fire ignition and during the flaming and smoldering phases of the burn.

This unique dataset provides insight towards how sub-canopy turbulent mixing, $PM_{2.5}$, CO_2, CO and other trace gases change both inside the unit, as the flaming front passes and outside the burn unit. These observation data are valuable because they provide a unified dataset that encompasses several smoke modeling steps, which is important for BlueSky Modeling Framework pathway evaluation. The objective of this research is to collect multiple comprehensive near-fire datasets and use these data to develop a new pathway through the Framework that is specifically designed for predicting low-intensity/smoldering smoke transport and dispersion.

Methods

Two research burns were accomplished, one with the full experimental design and a second with a subset of instruments designed to give additional observation data. Unit 14, 61-acres, and Unit 21, 46 acres, were accomplished on 07- and 09-Mar-2010. Terrain between the two units differed, with Unit 14 mainly flat and Unit 21 located on a hillside. Both units were burned with a backing fire. Fire line was raked around the instrument towers and heat shielding was wrapped around the tower legs to avoid direct contact of flames and to minimize heat exposure. Unit 14 and 21 were ignited at 11:20AM and 11:00 AM, respectively, the flaming phase of the burns was over at 3:20 PM and 2:45 PM, respectively. Ignition started from the north-eastern corner of both units.

Two meteorological towers were placed outside Unit 14 and were outfitted with horizontal and vertical wind, temperature, relative humidity, and light sensors. These data were used to characterize the overall meteorological activity in Calloway Forest. Vertical soundings of the atmosphere were taken with a radiosonde at the time of ignition and just after the flaming phase of the burn. A SODAR operated constantly during the burn to give vertical wind information from 0 to 200 m above ground level (AGL).

Burn Unit 14: Ten fuel sampling plots were placed in the unit and fuel types, moisture, and loadings were assessed prior to the burn. Post-burn consumption was analyzed by returning to these fuel plots and collecting the remaining fuels.

This unit was outfitted with several towers and extensively instrumented to obtain observations both inside and outside the burn unit (Fig. 1). Two tall towers (#1 and #2) were placed inside the burn unit and outfitted with turbulent, heat, and meteorological sensors. At each tower 4 tripods with CO sensors were deployed along NE-SW transects. Tower #1 was outfitted with CO_2 and heat flux instruments. An additional tall tower (Super Tower) was located outside and downwind from the burn unit. This tower was outfitted with turbulent, meteorological, and CO_2, CO, black carbon, NO, poly aromatic hydrocarbon (PAH), and tracer gas sensors. At this tower five $PM_{2.5}$ monitors were deployed along a transect. A tracer gas was released from within the burn unit through a line source. This gas was used to verify smoke dispersion parameters and to calculate emission estimates of other trace gasses.

Burn Unit 21: Due to an unseasonable set of El Niño induced winter snow storms (first in 20 years) we were unable to do more than one burn with our full experimental design. We were however, able to collect a supplemental dataset 2 days after Unit 14 was accomplished. This was an impromptu study and fuel data for this unit was not collected prior to the burn. This unit did not vary in a qualitative way from nearby units where fuel analyses were completed.

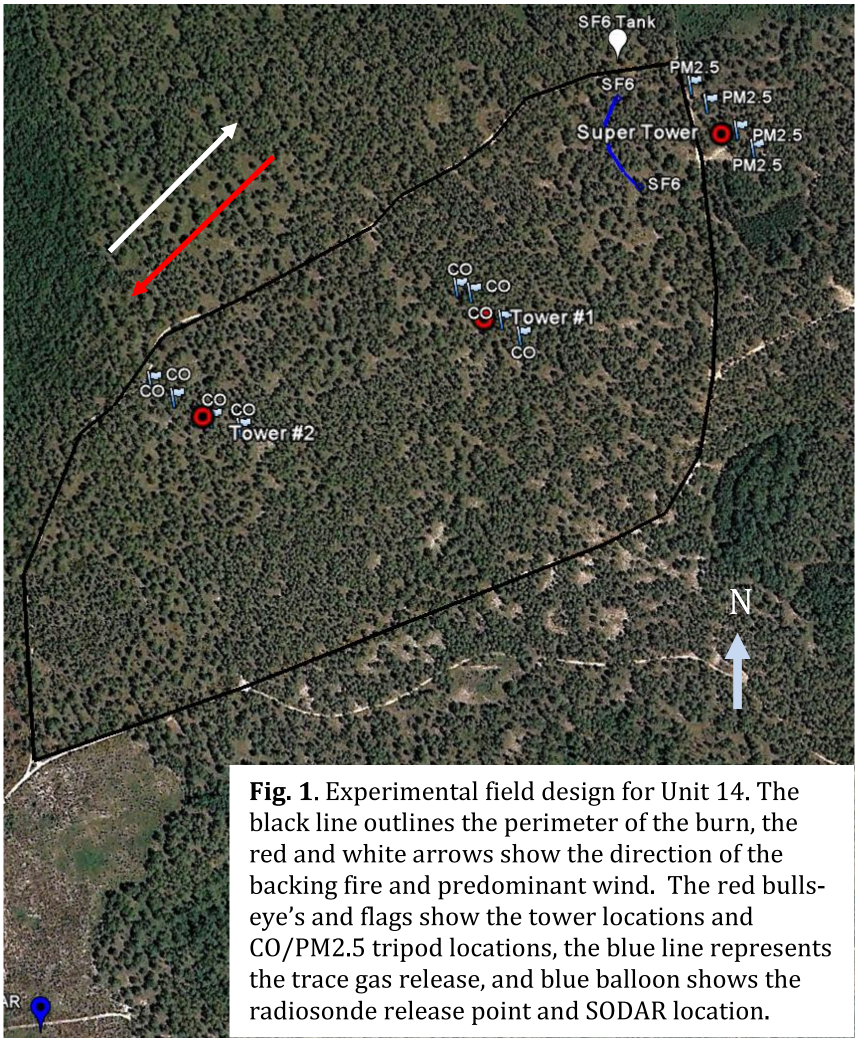

Fig. 1. Experimental field design for Unit 14. The black line outlines the perimeter of the burn, the red and white arrows show the direction of the backing fire and predominant wind. The red bulls-eye's and flags show the tower locations and CO/PM2.5 tripod locations, the blue line represents the trace gas release, and blue balloon shows the radiosonde release point and SODAR location.

Inside this unit, 1 tripod was placed in the center and outfitted with heat flux, CO_2, CO, and black carbon sensors. In addition, five $PM_{2.5}$ monitors were placed outside the unit and co-located with CO sensors. These instruments were located along the perimeter road downhill from the unit.

BlueSky Smoke Predictions: The BlueSky Modeling Framework was set up to run with its default pathway FCCS-CONSUME3.0-FEPS-CALPUFF for the duration of the possible burn widow (last week of Jan. to 2[nd] week in March). The daily 1-km dispersion predictions were posted to a website (today.airfire.org/nc1) every morning. One kilometer MM5 data were used to drive the dispersion model, the meteorological domain was centered over the Calloway Forest. The MM5 data was produced by Northern Research Station. Once the fuels data were collected the Framework pathway was modified to use the observed fuel types and loadings instead of the FCCS dataset. The modified fuel dataset was used for predictions for burn units 14 and 21.

Results

Fuel and Consumption Both units contained primarily 1-hr and 10-hr fuels of long leaf pine litter and wiregrass. There were a handful of 100-hr fuels and a couple of 1000-hr fuels in each unit. In Unit 14, the average pre-burn fuel moisture and dry weight was 29% and 3.14 tons per acre, respectively. The prescribed fire reduced the fuel loadings by 73% leaving 0.86 tons dry weight per acre.

Meteorology The meteorology during ignition varied little between units 14 and 21, on both days the maximum temperature ranged from 17 C to 20 C, wind speeds remained below 2.5 ms^{-1}, and relative humidity was ~18% and 27% for units 14 and 21, respectively (Fig. 2). During the Unit 14 burn the predominate wind direction was from the southwest, towards the Super Tower and $PM_{2.5}$ monitors. Winds shifted during the Unit 21 burn from a southwest direction to a southerly direction.

Vertical soundings of temperature and winds taken before and after the Unit 14 burn show a dry air mass aloft and a change in wind direction from northwest to west-southwest by the end of the burn (Fig. 3).

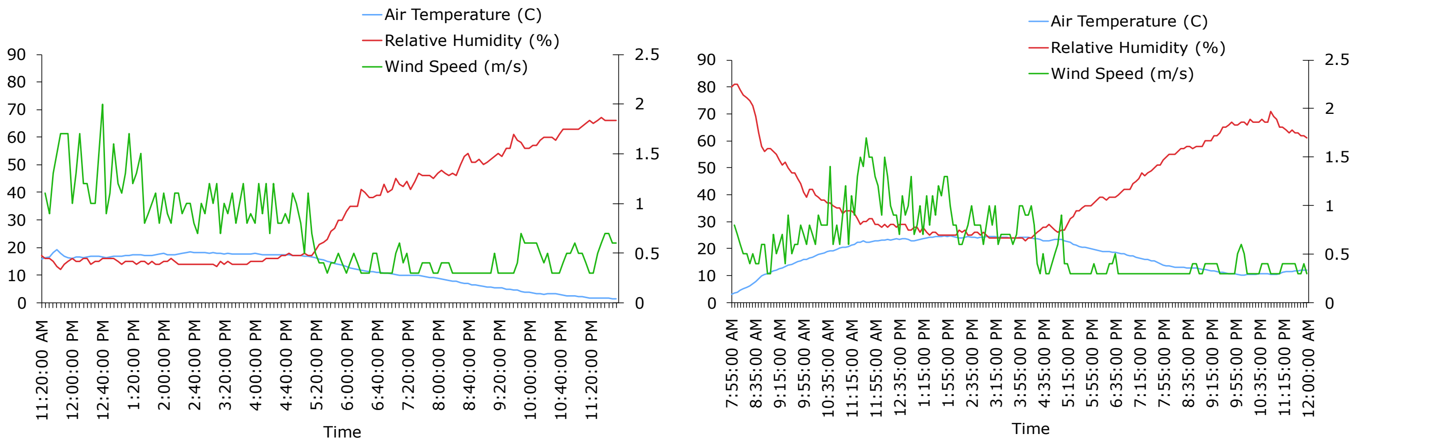

Fig. 2. Temperature and relative humidity (left axis) and wind speed (right axis) recorded at Units 14 (left) and 21 (right). Wind speeds below 0.4 m/s are considered calm and are represented by a straight line in the data; 1 m/s is ~ 2 mph.

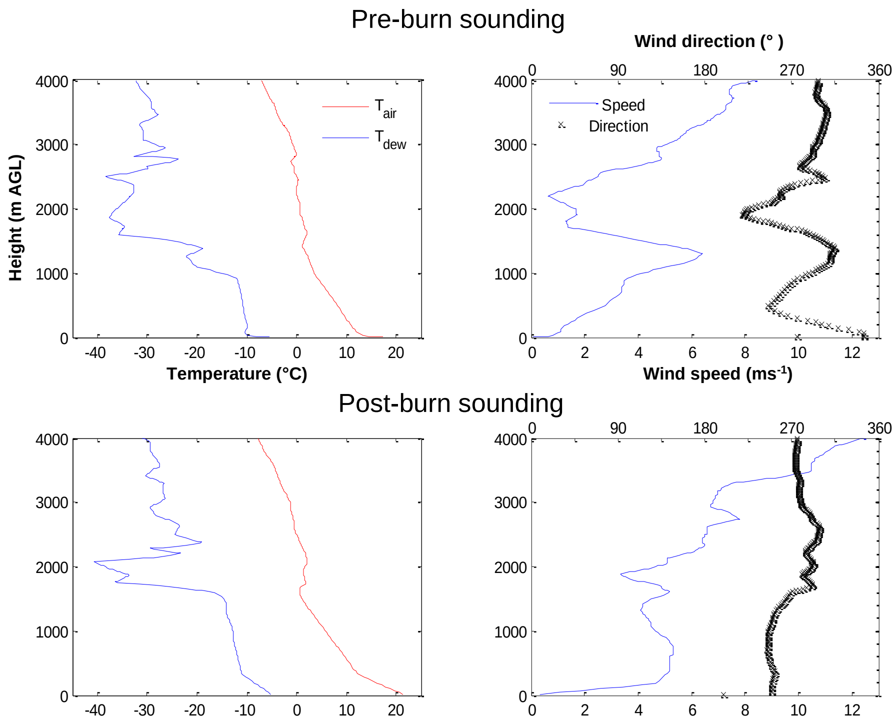

Fig. 3. Vertical soundings taken at ignition and just after the flaming phase of the unit 14 burn; Air (red) and dewpoint (blue) temperatures are shown on left and wind speed (blue) and direction (black) are shown on right.

CO and PM2.5 observations Carbon monoxide sensors located inside Unit 14 near the interior towers give a general picture of concentration trends during the flaming and smolder phases of the burn (Fig. 4). The flaming front went by the centrally located tower (Tower #1) at 1:00 PM and Tower #2 at 2:00 PM and CO concentrations peak sharply with the passing of the flaming front. These sharp peaks can be used to understand where the flaming front is located within the burn unit. The five-minute averages show higher than atmospheric background concentrations (< 1 ppm) starting near ignition (11:20 AM) and then slowly returning to background concentrations after 7:00 PM. US EPA standards for CO are 9 ppm over 8 hours and 35 ppm over 1 hour. No sensor recorded levels above the 8-hr standard and the 1-hr standard was only broken during the passage of the fire front. These concentration signatures are very different from those recorded at Unit 21 with sensors located just outside the burn perimeter (Fig. 5). Unit 21 CO concentrations show the elevated 'bubble' but no high peaks and no sensor went above the EPA threshold.

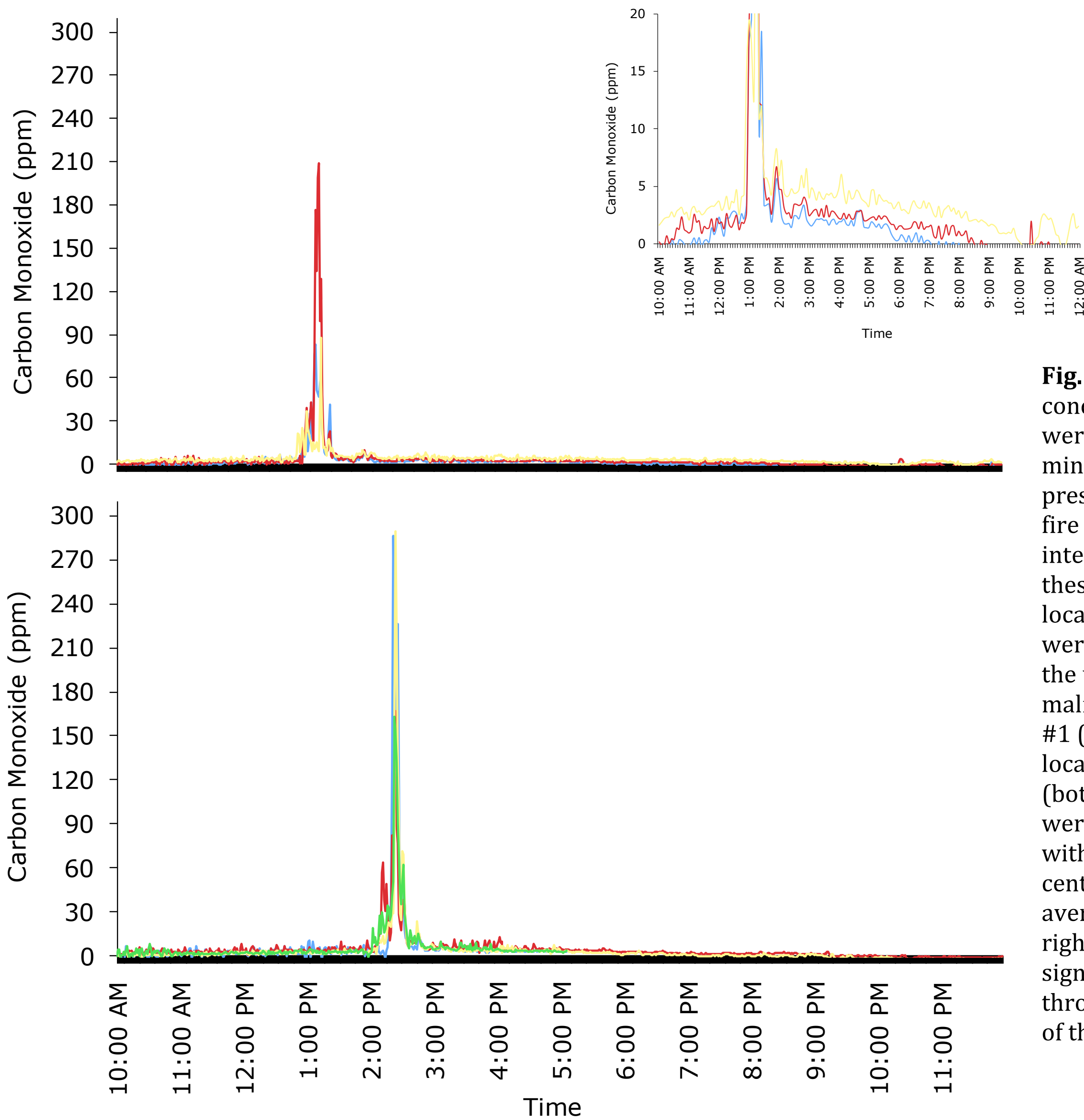

Fig. 4. Carbon monoxide concentrations (ppm) were sampled every minute in Unit 14 during a prescribed fire. A backing fire was used to ignite the interior of the unit where these sensors were located. Three sensors were near the center of the unit (one malfunctioned) at Tower #1 (top) and four were located near Tower #2 (bottom). The sensors were placed 25 m apart with the tower at the center. Five minute averages of the data (top-right) show an elevated signature of CO throughout the duration of the burn.

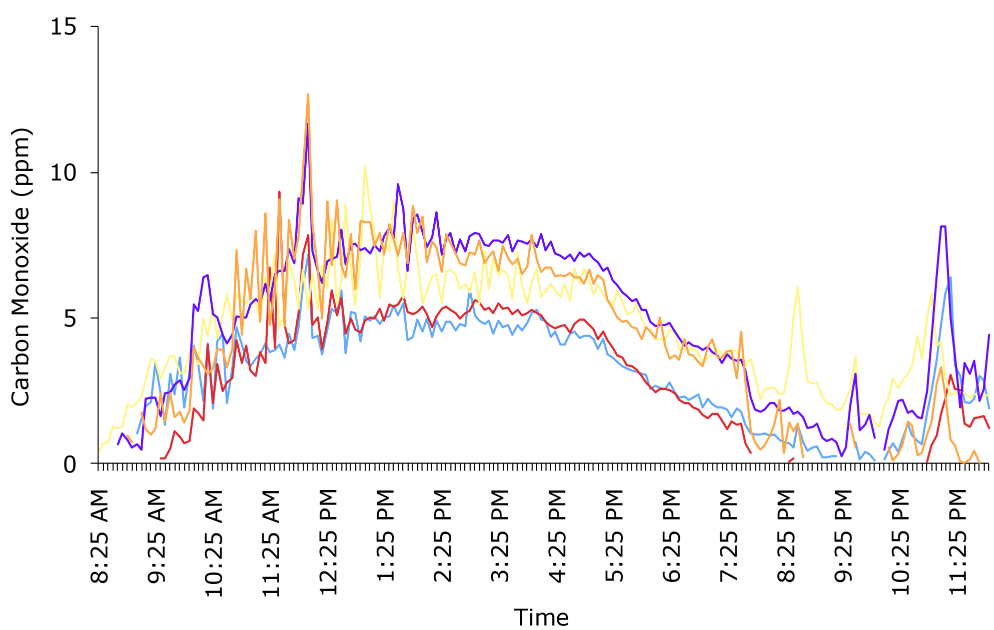

Fig. 5. Five minute CO averages (ppm), measured just outside Unit 21 by five sensors that were placed 20 m apart on the downhill side of the unit perimeter. Ignition was at 11:00 AM and the flaming phase of the burn was over at 2:45 PM.

Fine particulate (PM2.5) monitors measured concentrations just outside the Unit 14 burn perimeter at the Super Tower site (Fig. 6). Initial concentrations are high at the time of unit ignition and as the perimeter black line was ignited near the monitor locations (11:20 AM to 11:40 AM). After the perimeter line passed the monitors, the concentrations fluctuated as the smoke plume traveled from the interior of the burn unit towards the monitors. The peaks are less and the duration of elevated concentrations shortens as the ignition progresses further away from the Super Tower site. Nighttime concentrations are high due to smoldering of the 1000-hr fuels, low wind speeds and a decrease in the atmospheric mixing height. The concentrations from all five monitors follow the same trend, indicating that they are all near the smoke plume centerline.

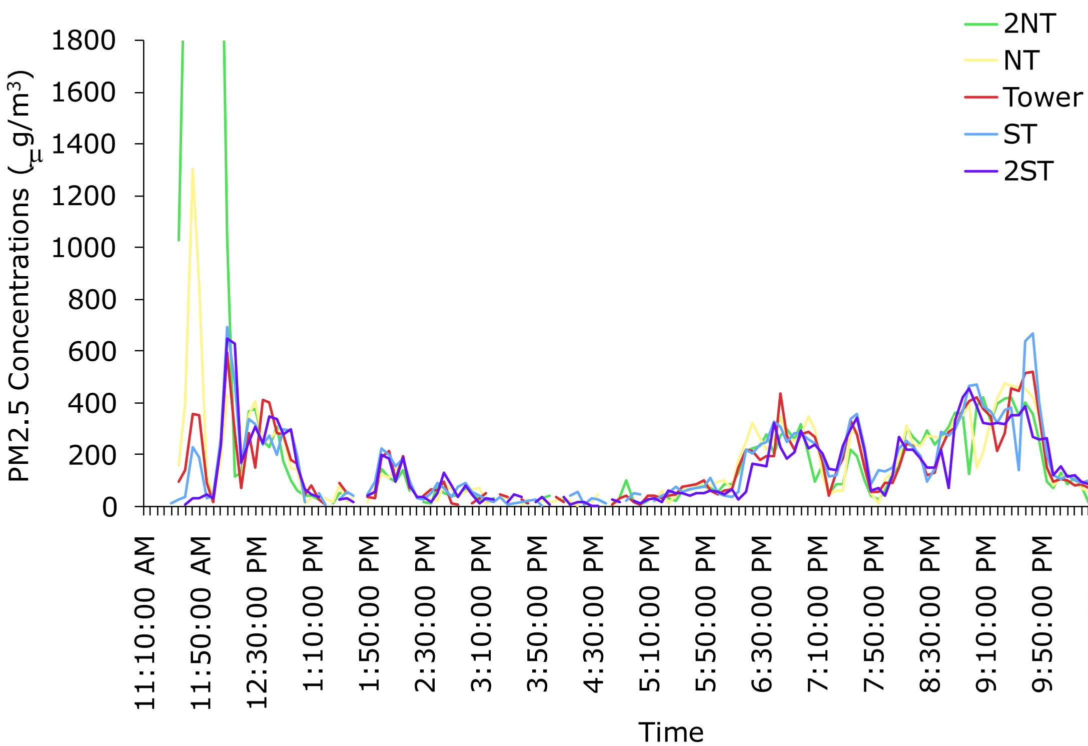

Fig. 6. PM2.5 concentrations recorded just outside the burn perimeter during a prescribed burn in Unit 14. Ignition started at 11:20 AM and the flaming phase ended at 3:50 PM. The monitors were located at the Super Tower site and placed 25 m apart; 2NT is the northern most monitor and 2ST is the southern-most monitor.

The concentration trend from Unit 21 differs from Unit 14; the wind shifted slightly during this burn and pushed the centerline of the smoke plume in a more northerly direction, missing most of the monitors. The resulting data from Unit 21 shows plume edge effects as the smoke plume edge meandered back and forth over the monitors. This is evident as peaks from single monitors rather than all monitors simultaneously peaking (Fig. 7), as was the case with Unit 14. The meandering signature continues into the smoldering phase of the burn until nighttime downslope advection takes over, pushing the smoke from the smoldering fuels downhill and towards the monitors. All monitors begin to track similar peak concentration trends (~9:15 PM) when this occurs. Nighttime smoldering concentrations are much higher for this case, likely due to the pooling of the smoke at the bottom of the hill.

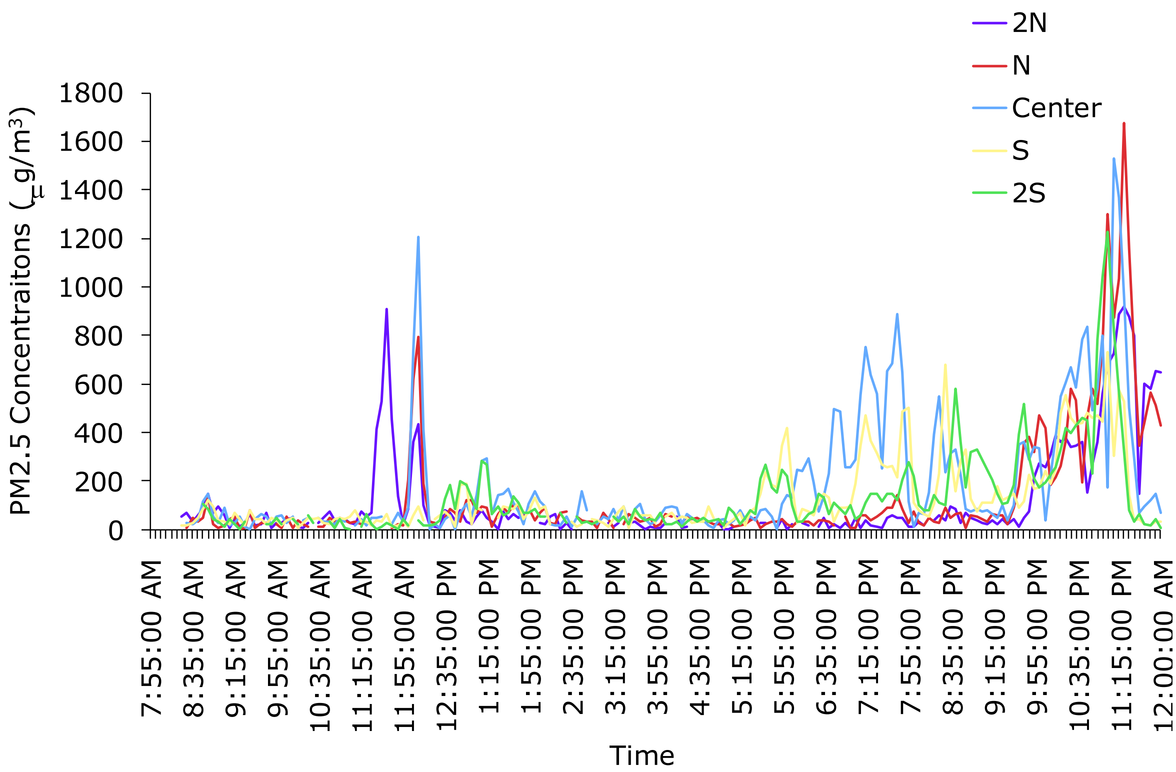

Fig. 7. PM2.5 concentrations recorded just outside the burn perimeter during the Unit 21 hillside burn. Ignition started at 11:00 AM and the flaming phase ended at 2:45 PM. The monitors were placed 20 m apart just outside the unit and on the downhill side; 2N is the northern-most monitor and 2S is the southern-most monitor.

Heat, black Carbon, NO, and CO2 observations Vertical profiles of temperature were made in- and outside of Unit 14 at Tower #1 and the Super Tower. Both profiles show the primary plume aloft starting at ~14 m and extending beyond 30 m (Fig. 8). The interior tower recorded a definite shift in temperature from pre-flaming front of 13 C to post-flaming front of 16 C. As the flaming front moved past the interior tower temperatures went above 50 C at 2 m AGL. The cooler temperatures around 12:59 PM are likely due to entrainment and the downward mixing of cooler air from above the canopy, this is indicated by the 10 m W component of the wind velocities (see Fig. 12). The radiative heat flux measured at Tower #1 is ~35 to 40% of the total heat flux intensity as compared to ~40 to 50% of the total heat flux intensity for Unit 21 (Fig. 9). Assuming that the fuels between the two units are similar, the differences in the heat flux intensity can be explained by the topographic effect. The heat flux sensors were deployed on a small hilltop in Unit 21, and the flame moved upslope toward the sensor. Unit 14 was in primarily flat terrain.

Black carbon concentrations, observed at the Super Tower site expectedly trend similar to the PM2.5 concentrations. Black carbon is usually 2.5 microns or smaller and is one of the many particulate species measured by PM2.5 monitors. The initial sharp peak immediately occurs after the start of ignition (Fig. 10), which was near the instrument location. During this peak, black carbon makes up approximately 10% to 15 % of the PM2.5 concentrations measured at the same location. Black carbon concentration peaks continued to occur throughout the duration of the flaming phase of the burn and peak maxima did not lower as the ignition progressed away from the tower. This differs from the CO2 and NO measured at the Super Tower (Fig. 9), which both had an initial peak in concentrations near ignition, however the subsequent concentration peak maxima lower as the backing fire travels away from the instrument locations.

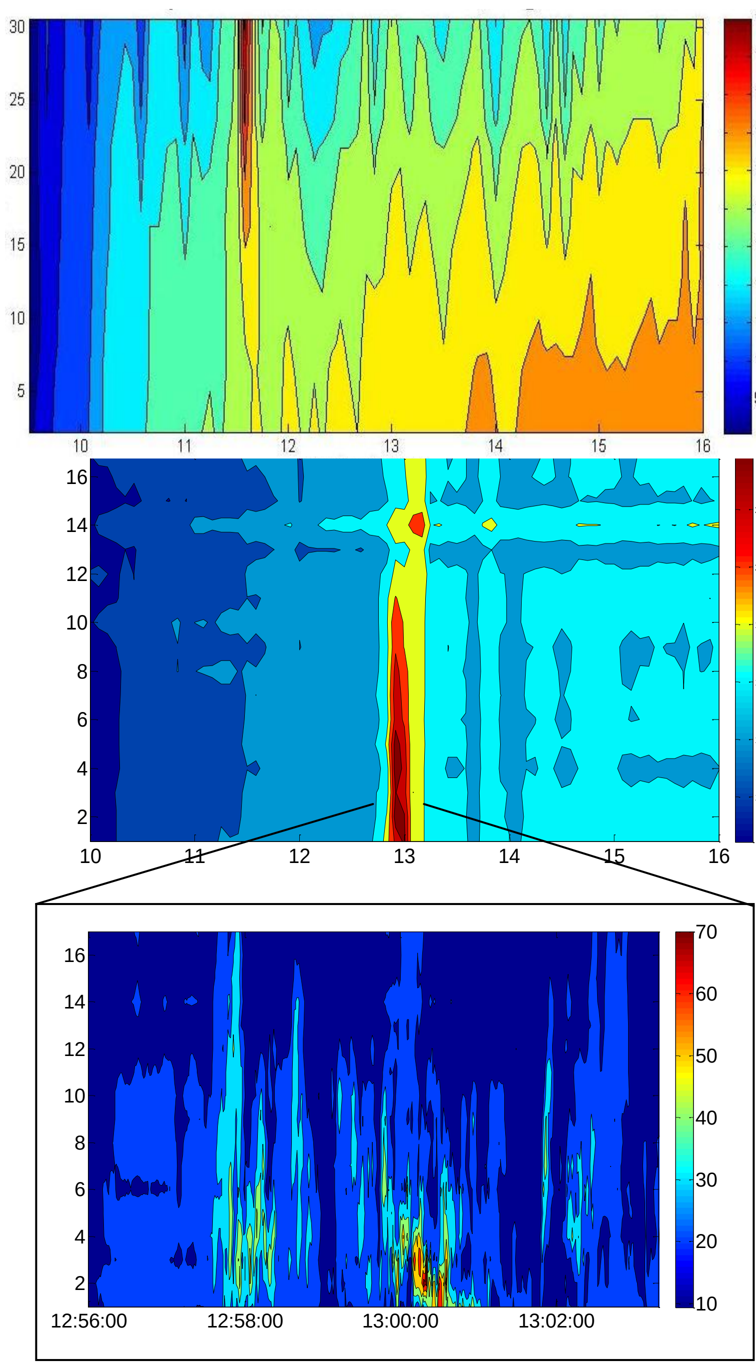

Fig. 8. Vertical profiles (height in m on left axis) of temperature (C) measured at the Super Tower (top) and interior Tower # 1 (middle) over the course of the burn (time on x axis). A fine temporal view of the flaming front passage under Tower # 1 is also shown (bottom). Note the different temperature scales, with the Super Tower ranging from 8 to 19 C, Tower #1 ranging from 11 to 24 C, and the temperature scale for the passage of the fire-front ranges from 10 to 70 C.

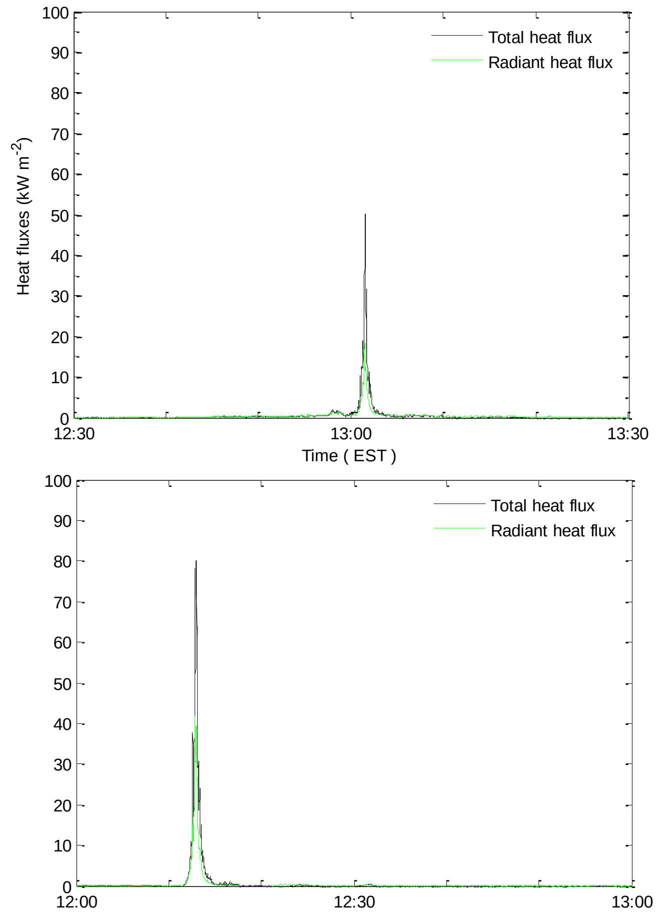

Fig. 9. Time series of total (black) and radiative (green) heat flux measured near the ground for Units 14 (top) and 21 (bottom). The data were collected every second.

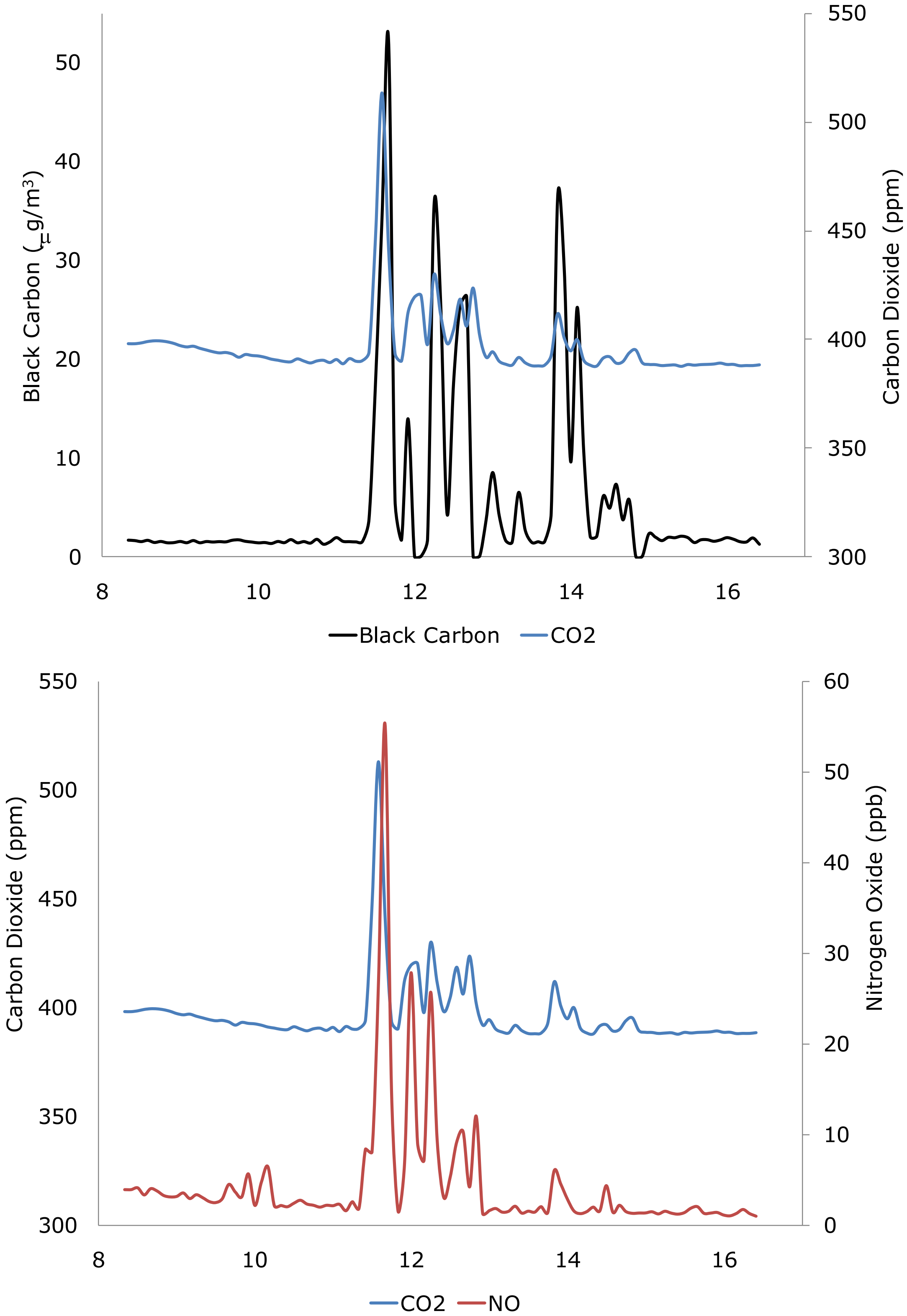

Fig. 10. Black carbon (μg/m³), CO2 (ppm) and NO (ppb) concentrations measured at the Super Tower site near the Unit 14 prescribed burn. Initial ignition at 11:20 AM was near the site and the backing fire progressed upwind and away from the tower location. The flaming phase of the burn was completed at 3:20 PM (15:20).

Carbon dioxide and monoxide concentrations were measured in the interior of units 14 and 21 at Tower #1 at 10 m AGL and on a tripod at 3 m AGL, respectively (Fig. 11). Since these sensors were mounted at different heights comparison of concentration magnitudes between units is not possible, however both display correlated trends between CO2 and CO. This is expected as CO is an indication of incomplete combustion, while CO2 is a sign of complete combustion. Both units show the sharp increase in CO as the flaming front passes near the sensors.

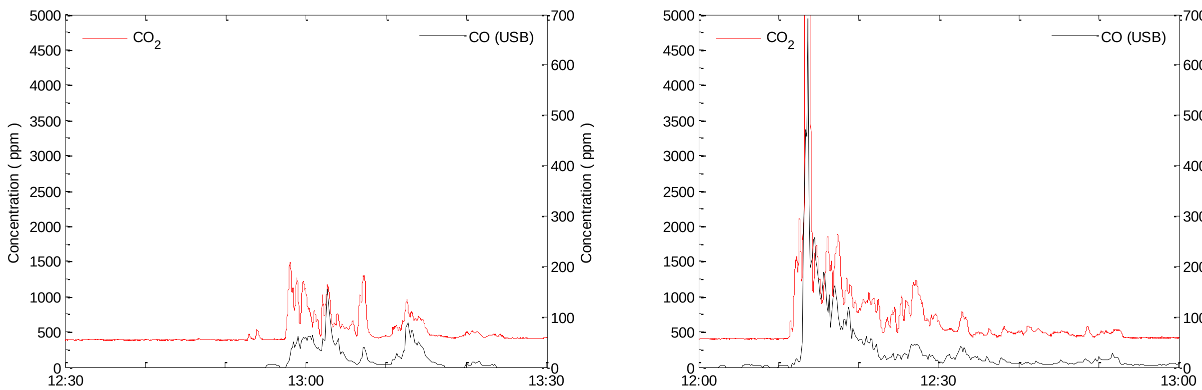

Fig. 11. Time series CO (black, right axis) and CO2 (red, left axis) measured at ~10 m in Unit 14 (Left) and ~3 m in Unit 21.

Turbulence under the Canopy Turbulence data were collected before, during, and after the prescribed burn at all of the towers. These data help to assess the interaction between winds and fire and to show the deviation from the natural sub-canopy turbulent eddies towards fire induced eddies. The two interior towers show similar turbulent signatures with the passage of the fire-front, particularly with the vertical wind component, W, and temperature (Fig. 12). With passage of the fire –front Tower #1 measured a stronger updraft near the ground (3 m height) due to the higher surface temperatures, in contrast, Tower #2 measured a stronger updraft aloft, likely due to the buoyant force of acceleration generated by the heat below the tower. Both towers experienced up- and downdrafts (seen in the W component), caused by buoyancy from the heat of the fire and entrainment of cool air above the canopy mixing down. The U and V horizontal wind velocities from the 3- and 10-m heights show a similar structure (Fig. 13), this occurs at both towers during and after the fire front passage (13:00 and 14:00). After passage of the fire-front the U wind velocity component exhibits definite structure with sign changing going from positive to negative. This indicates a change in wind direction, likely due to the thermal differences between the fire and the atmosphere at the tower. This signature occurs at both towers.

Trace gas concentrations The trace gas, SF6 released during the burn from a line source located inside Unit 14, was measured downwind at the Super Tower site. Measurements were made in the vertical along the tower and in the horizontal at the PM2.5 monitor locations. The tracer is an inert gas that can be measured at very low concentrations and is used to characterize plume dispersion characteristics. These data will eventually be used to help quantify emissions from the burn unit. During the burn, trace concentrations were recorded at the tower on several occasions (Fig. 14) including the initial ignition peak measured by all instruments. The high concentrations prior to the burn (pre-11:20AM) indicate that the wind direction was favorable for the experimental design. High tracer concentrations towards the end of the burn indicate that the wind was coming from the burn unit towards the tower, however only black carbon and PM2.5 concentrations register elevated peaks during these elevated SF6 concentrations.

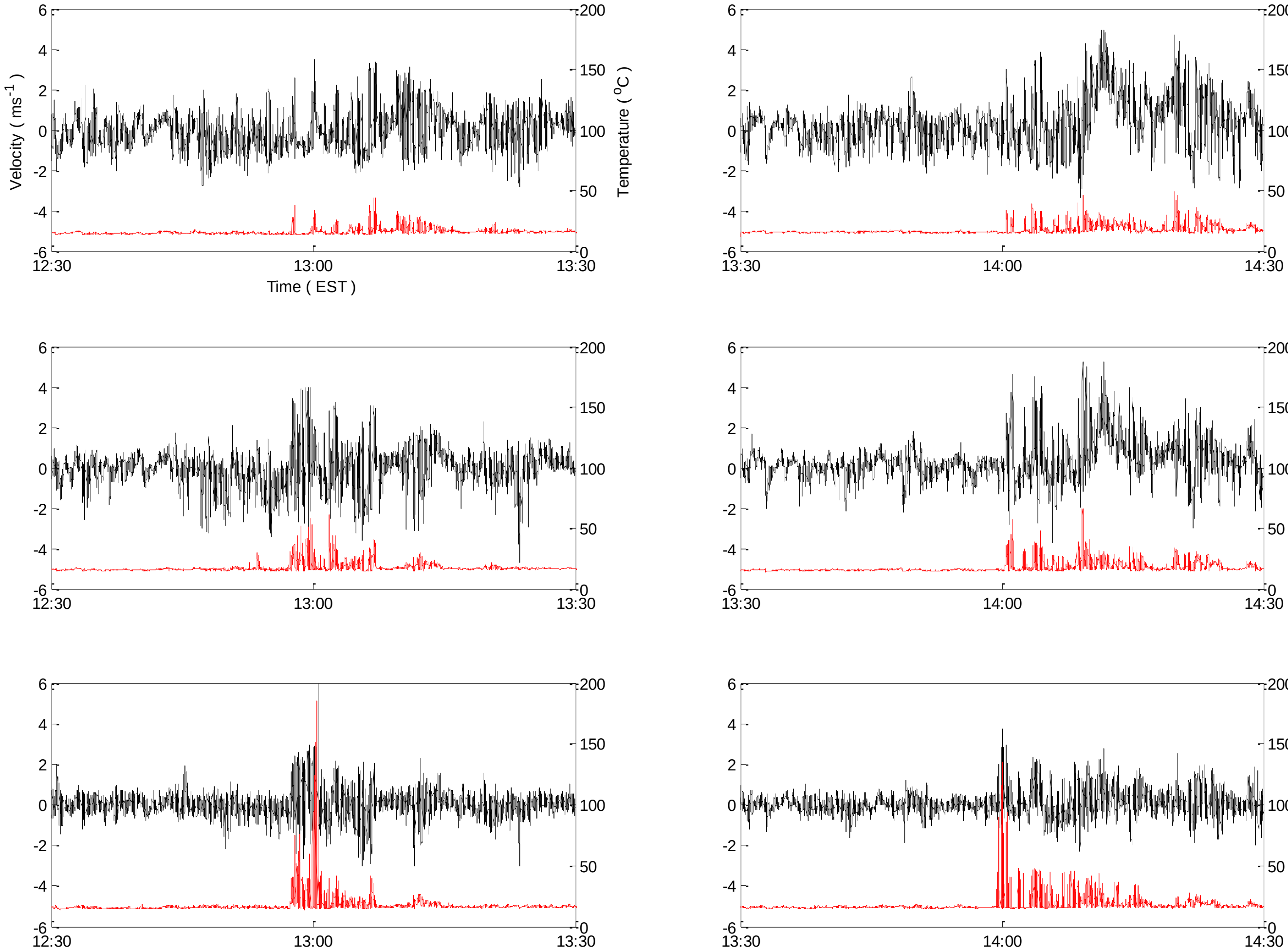

Fig. 12. Temperature (C, red, right axis) and the vertical wind velocity component, W (m/s, black, left axis), both measured with the sonic anemometers at 10 Hz (10 measurements per second), for the period surrounding the fire-front passing below Tower #1 (left) and Tower #2 (right). Measurements were made at ~20 m (top), ~10 m (middle) and ~3 m (bottom) AGL.

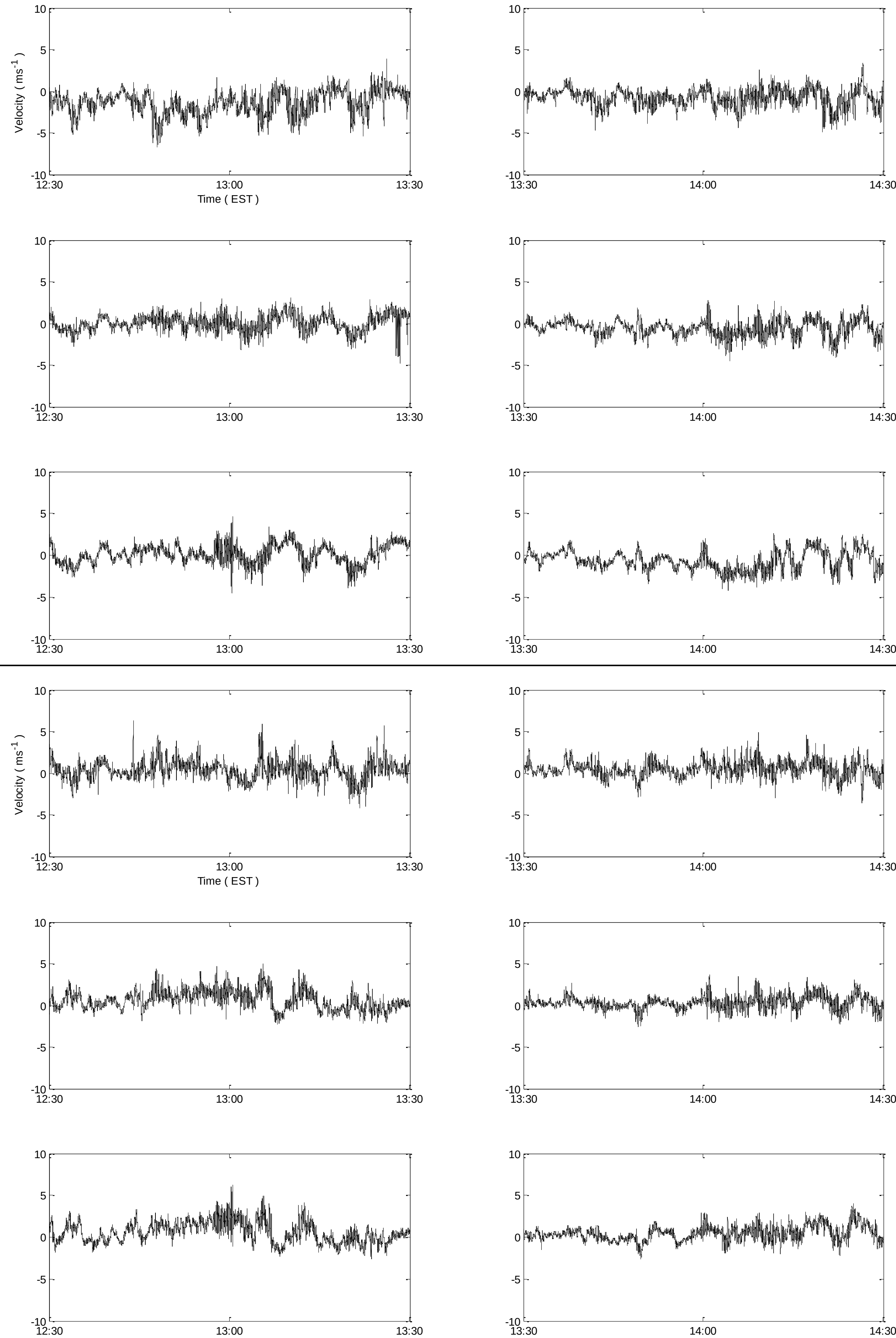

Fig. 13. The horizontal wind velocity (m/s) components U (top three) and V (bottom three) for Tower's #1 (left) and #2 (right). The instruments were located at ~ 20 m, 10 m, and 3 m AGL and are shown from highest to lowest per component.

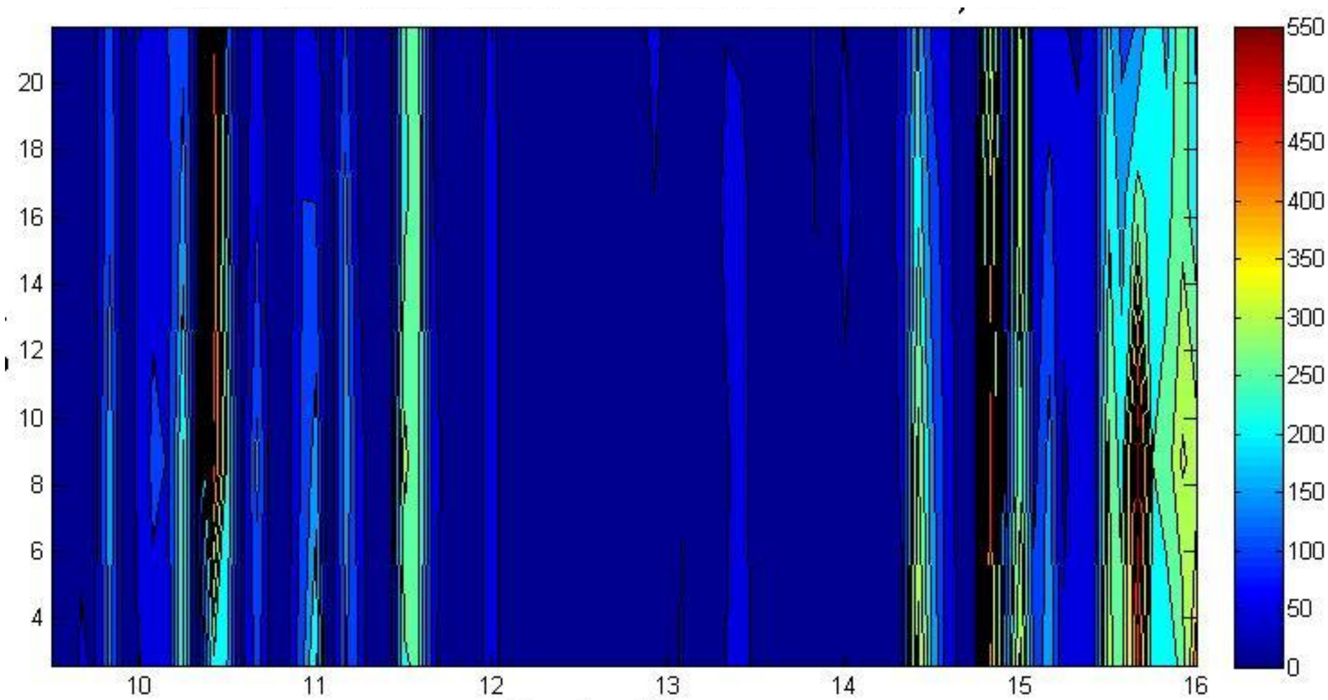

Fig. 14. Vertical (height, m on left axis) distribution of trace gas concentrations (SF6, ppt) at the Super Tower site. The trace gas was released from a 100 m line source within Unit 14 during the prescribed fire. Ignition occurred at 11:20 AM (Time, on x axis) and the plume hit the tower shortly after at 11:30 AM.

Concluding Remarks

Good observations were made during the Unit 14 burn. These are preliminary results and further analyses are required in order to make significant conclusions. The data from Unit 14 will be used to evaluate the dispersion predictions made by the BlueSky Framework and will be used to develop a new pathway for low-intensity smoke dispersion. Although the Unit 21 dataset is not as comprehensive as the Unit 14 dataset, it provides additional information on how PM2.5 concentrations change due to terrain (hill vs. flat) and smoke footprint properties (plume fringe vs. center).

Acknowledgments

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