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Observed Water Vapor Enhancement in Smoke Plumes

Caroline Marie Kiefer
San Jose State University

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OBSERVED WATER VAPOR ENHANCEMENT IN SMOKE PLUMES

A Thesis

Presented to

The Faculty of the Department of Meteorology and Climate Science

San José State University

In the Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Caroline M. Kiefer

May 2010

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The Designated Thesis Committee Approves the Thesis Titled
OBSERVED WATER VAPOR ENHANCEMENT IN SMOKE PLUMES

by

Caroline M. Kiefer

APPROVED FOR THE DEPARTMENT OF METEOROLOGY AND CLIMATE
SCIENCE

SAN JOSÉ STATE UNIVERSITY

May 2010

Dr. Craig B. Clements	Department of Meteorology and Climate Science
Dr. Robert D. Bornstein	Department of Meteorology and Climate Science
Dr. Brian E. Potter	USDA Forest Service

ABSTRACT

OBSERVED WATER VAPOR ENHANCEMENT IN SMOKE PLUMES

by Caroline M. Kiefer

Wildland fires cause the loss of life and billions of dollars in property damage every year in the US annually; thus, there is a need to better understand, predict, and manage both wildland and prescribed fires. Moisture released from combustion, in addition to added heat, can enhance buoyancy and convection, influencing fire behavior. Previous studies have shown a wide range of smoke plume moisture enhancement, but much uncertainty still exists in the quantitative values of moisture released during combustion. In this study, three measurement platforms were used to obtain *in situ* measurements of temperature and relative humidity during various prescribed fires near the fire front and aloft. Stationary and non-stationary measurement platforms used were towers equipped with temperature and relative humidity probes, radiosondes, and a radio controlled (RC) airplane with a radiosonde installed in the wing. The goal of this study is to better quantify moisture of wildland fire smoke plumes.

Water vapor concentration varied within the smoke plume from the surface and aloft. Water vapor captured by the radiosondes aloft was less than that obtained by the towers at the fire front, as a result of ambient air entraining into the smoke plume at higher levels. Tower and radiosonde results show smoke plume moisture enhancement ranged between 1.0 to 19.1 g kg⁻¹ and 0.3 to 2.5 g kg⁻¹, respectively. Smoke plume moisture enhancement captured by the RC airplane is on the order of 0.5 to 4.3 g kg⁻¹, in agreement with the tower data from the same burn.

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1. Introduction

Natural wildfires cause billions of dollars of damage every year in the US due to unpredictable and unmanageable fire spread. According to the 2008 Climate Wildfire Season Summary from the National Climatic Data Center (NCDC 2009), total burned areas exceeded five million acres with damage over \$1B. While wildfires in 2006 and 2007 caused even more damage than 2008, increasingly drier climates associated with climate change predicted by Global Circulation Models (GCM) suggest fire frequency will increase by 11-55% from 2077-99 (Luers et al. 2006). Understanding wildfire dynamics is essential to better control and contain natural and prescribed fires in the safest way possible.

Byram (1959) was first to analyze fire behavior to identify fire severity by diagnosis of the amount of vegetation destruction and resistance to suppression. It was known long ago that wood burning, during combustion, emits water vapor and carbon dioxide into the atmosphere due to its hydrocarbon composition. Byram observed that latent heat of vaporization near the fire acts as an energy sink at low levels, but it may serve as an energy source at higher levels. Few studies have since considered the impact of moisture on plume convection as a result of moisture released from combustion, as it is believed to be small in magnitude when compared to fire-induced temperature increases. Numerical modeling studies show that natural wildland fires produce heat anomalies sufficient to create horizontal and vertical buoyancy gradients that can affect fire spread by the mixture of ambient air into the fire plume and increased flame temperatures (Jenkins et al. 2001). Clouds, rain, and even thunderstorm development have been

observed in the vicinity of large open fires (Simard et al. 1983; Stocks et al. 1996; Fromm et al. 2006, Cunningham and Reeder 2009).

Potter (2002) proposed that the circulation generated at the fire front starts during the deepening stage when the fire creates an updraft that is countered by a resulting nearby downdraft. He then analyzed plume stability by means of the Convective Available Potential Energy (CAPE), which is the acceleration induced by buoyancy forces in moist air. Theoretically, moisture enhancement in smoke plumes is supportive of convection, while surface conditions remain dry enough for horizontal fire spread.

To approach this moisture release within smoke plumes, Potter (2005) revisited many large-scale forest fires that dated back to early studies on fire behavior. He focused on cases that resulted in pyrocumulus cloud formation above smoke plumes. The bottom of the cloud is considered the lifting condensation level (LCL), and the top of a cloud is the equilibrium level (EL). In most cases analyzed, these heights were estimated visually through photographs. The LCL and EL over fires were compared to archived soundings of ambient LCL and EL conditions where smoke was not present. Potter found the LCL to be up to 860 m lower over fires than ambient conditions which would require adding more than 4 g kg^{-1} of moisture. Other cases revealed a plume height up to 13 000 m where the ambient EL only reached 9 900 m, which requires a combination of 3 g kg^{-1} and 3°C of moisture and heat, respectively. The lower LCL and higher EL imply increased moisture in smoke plumes strengthens convective columns above fires.

Potter (2003) developed a bulk aerodynamic theoretical model to estimate fire plume moisture enhancement and to express the change in water vapor mixing ratio, Δq_v ,

as a result of fuel combustion. The model has been altered (Clements et al. 2006) to compare to observations, and is given by,

$$\Delta q_v = 100 \frac{f u_f (0.56 + M)}{H_M (u - u_f)} , \quad (1)$$

where f represents fuel load, M is fuel moisture content, H_M is the layer of the atmosphere affected by the plume, and u and u_f are wind speed and fire spread rate, respectively. Observations from natural forest fires used in (Eq. 1) estimated a range of increased water vapor mixing ratio on the order of 1-3 g kg⁻¹.

Dynamics associated with low-level cloud formation in the vicinity of prescribed and natural fires introduce another motivation for study, as they have been known to inhibit highway visibility and threaten safety (Mobley, 1989). Increased highway accidents associated with poor visibility from smoke plumes motivated Achtemeier (2006) to study fog production in the vicinity of prescribed fires. He measured smoke temperature and moisture with thermocouples and a temperature and relative humidity probe, respectively, at three sites in the Southeast US during experimental and prescribed burns. Results show increased water vapor mixing ratios range from ~ 3-40 g kg⁻¹. When water vapor enhancement was compared to temperature fluctuations, hotter smoke seemed to emit more smoke plume moisture.

Achtemeier (2006) calculated moisture excess values by considering the difference of moisture volume-flux for smoke from that of ambient air. Moisture excess combines average smoke moisture with ambient air water vapor mixing ratio to estimate the smoke moisture in air leaving the plume. It was found that the contribution of smoke

plume moisture is higher during a large burn with a shallow mixing layer and weak surface winds. These conditions occur most often at night, when relative humidity is high and temperatures are low. This implies additional moisture from smoke plumes increases fog density and allows for fog formation in conditions that would have not otherwise produced fog. Liquid water content for usual fog formation ranges from $0.001\text{--}0.30\text{ g m}^{-3}$, whereas results found in smoke environments range from $0.07\text{--}5.1\text{ g m}^{-3}$ (Achtemeier 2008).

Grass fire experiments held in Texas (Clements et al. 2006, 2007), captured plume moisture data with a tethered sonde system. Tethered sonde data shows water vapor increased by $1\text{--}2\text{ g kg}^{-1}$ in low levels of the smoke plume, but it remained relatively unchanged at 90 m, to imply an existence of a strong vertical water vapor gradient above the fire. These results are lower than $3\text{--}40\text{ g kg}^{-1}$ found by Achtemeier (2006), but agree with $1\text{--}3\text{ g kg}^{-1}$ found by Potter (2002).

Numerical modeling studies have also focused on understanding fire-induced buoyancy and convection on small spatiotemporal scales. Kiefer et al. (2008, 2009) discovered that a fire-induced multicell is a series of buoyant bubbles advected by background environmental flow. They hypothesized that overall convection intensity is dependent on the advection by upstream wind throughout the depth of the mixed layer and the heating of surface air parcels by the fire. Buoyancy and advection parameters were established to analyze convection near a fire source. They found that as surface wind speed increased (decreased), air parcels received less (more) heat and penetrated less (more) in the vertical. These studies neglect the buoyancy effects from released

moisture due to combustion and focus on the drastic temperature anomaly at the fire. These parameters are incomplete without the inclusion of moisture released within the smoke plume.

According to Parmar et al. (2008), moisture is released from two different sources: release of fuel moisture that is not chemically bound to the organic molecules of the fuel and production of water vapor by chemical reactions during combustion. In 2003, they studied 16 burns in a laboratory to determine which source takes greater precedence. They discovered that combustion of different vegetation fuels is not a homogeneous process and each fuel differs in flaming and smoldering durations, thus, the hypotheses were difficult to test. A 0.75 water formation per carbon ratio was found and that water comes from within the inside cells of the vacuoles. As a result, traditionally oven-drying fuel can underestimate fuel moisture content, which leads to a lower percentage and a greater impact on released moisture from combustion.

Observations of severe convective storms initiated by intense wildfires in Australia were simulated by Cunningham and Reeder (2009) to understand the role of the fire on the pyro-convection and pyro-tornadogenesis. They found water production from the fire is critical in the development of a pyro-cumulonimbus cell strong enough to reach the tropopause and plays a significant role in the associated tornadogenesis.

The role of moisture released from fires and its effects on plume buoyancy and convection have been criticized. Fire-atmosphere interactions were modeled in a recent study (Luderer et al. 2009) to compare the influence from the fire on the LCL and to decipher between two theories. The first is an increase in surface temperature near the

fire results in a higher saturation vapor pressure and delayed condensation, or a higher LCL, while the second states an increase in moisture released from the fire results in a lower LCL. Numerical model simulations show that water vapor emitted from the fire is rapidly diluted below the LCL. They also found that realistic values of water vapor and condensed water produced during combustion both have a lesser impact on plume convection than fire-induced temperature increases, which act to raise the LCL. To simulate results found by Potter (2005), water vapor mixing ratios were on the order of 6 times greater, ranging from 6.6-35 g kg⁻¹. The authors claimed this water vapor enhancement is unrealistically high, but these results are within range of that measured by Achtemeier (2006).

Previous studies have shown a wide range of smoke plume moisture enhancement, much uncertainty still exists in the quantitative values of moisture released during combustion. Some studies used theoretical models to estimate plume moisture enhancement, others took measurements of small scale burns at the surface, and *in situ* tower-based surface measurements of a passing fire. This study focuses on moisture measurements obtained directly inside small-scale, prescribed fire smoke plumes by use of a radio controlled (RC) model airplane to obtain temperature and relative humidity measurements up to 400 m AGL. Additionally, more traditional methods of data acquisition are utilized in this study and include tower based measurements in direct passage of fire fronts as well as radiosonde data obtained from weather balloons launched downwind of prescribed burns. Therefore, this study provides a detailed dataset for examining plume moisture enhancement at the fire front and aloft, which can be used to

better understand fire-atmosphere interactions. Temperature and relative humidity measurements allow for calculated water vapor mixing ratio values. These will be compared to background conditions to quantify the amount of moisture released from smoke plumes and added to the atmosphere during natural wildland fires. This process of calculations will be described in the Methods section. Results from tower, radiosonde, and RC airplane measurement platforms will be presented in the Results section and followed by Conclusions and Future Work.

Results from this study will help identify how smoke plume moisture changes with height. Instruments that are secured on towers, hand held, and attached to a tether sonde are stationary and limited in height, thus, they cannot capture upper-level effects of smoke plumes on ambient conditions. A radio controlled airplane allows for an examination of plume moisture as it mixes vertically and horizontally while entraining ambient air into the smoke plume. A comparison of smoke plume moisture enhancement will be made for burns in different vegetations and climates. Plume moisture enhancement associated with higher versus lower intensity burns will also be examined.

2. Methodology

Three measurement platforms were used to obtain *in situ* measurements of smoke plume moisture during various prescribed burns to better understand fire-atmosphere interactions. Two towers were deployed during the FireFlux experiment (Clements et al. 2007) to measure fire-atmosphere interactions as a prescribed grass fire passed towers equipped with temperature and relative humidity probes. Ambient conditions were captured before ignition, then smoke plume measurements were obtained due to downwind placement of the towers, and lastly fire front passage was captured.

Weather balloons with attached radiosondes were launched during prescribed fires to capture smoke plume characteristics. Ambient environmental soundings were obtained before ignition and after the burning stage was complete, and radiosondes launched during plume development measured the smoke environment. Tower and balloon measurements were obtained during the Prescribed Fire Emissions Experiment (R_xFEmEx) that was conducted in July 2008 (herein referred to as Summer) and January 2009 (Winter) at the Joseph W. Jones Ecological Research Center in Ichauway, Georgia.

The third measurement platform utilized in this study was a small, inexpensive radio controlled airplane with a radiosonde installed in one of its wings. It was used to obtain temperature and relative humidity measurements inside the smoke plume of a prescribed fire at Joseph D. Grant Park in the Diablo Range of California on 7 October 2008. Temperature and relative humidity were also measured on a tower placed inside the burn unit at Grant Park. Refer to Table 1 for name convention for all burns discussed in this paper.

Table 1. Experiment Abbreviations: Name convention for all burns.

Name	Date	Experiment
FF	23 Feb 2006	FireFlux
S1	15 July 2008	R _x FEmEx
S2	16 July 2008	R _x FEmEx
S3	17 July 2008	R _x FEmEx
GP	7 Oct 2008	Grant Park
W1	12 Jan 2009	R _x FEmEx
W2	13 Jan 2009	R _x FEmEx
W3	14 Jan 2009	R _x FEmEx

a. Calculations

Water vapor mixing ratio, q , is the ratio of mass of water vapor to mass of dry air (Stull 2000) and it was calculated to determine the amount of moisture released during various prescribed burns. It is given by,

$$q = \frac{\varepsilon \cdot \theta}{P - \theta} \quad , \quad (2)$$

where ε is the ratio of the dry air gas constant to water vapor gas constant ($= 0.622$ g_{vapor}/g_{dry air}), atmospheric pressure is P , and θ is the partial pressure of water vapor. Measured temperature and relative humidity from the Vaisala HMP45C (referred to hereafter as HMP45C) temperature and relative humidity probe, as well as that obtained from the radiosonde, were used in the Clausius-Clapeyron equation to calculate the saturated vapor pressure, θ_s ,

$$\theta_s = \theta_o \cdot \exp \left[\frac{L}{R_v} \cdot \left(\frac{1}{T_o} - \frac{1}{T} \right) \right] \quad , \quad (3)$$

where temperature T was obtained from both the HMP45C and radiosonde, L is the latent heat of vaporization ($= 2.5 \times 10^6$ J kg⁻¹), R_v is the gas constant ($= 461$ J K⁻¹ kg⁻¹), and

constant parameters e_o ($= 0.611$ kPa) and T_o ($= 273$ K). Once e_s was found, e was calculated based on the relationship

$$\frac{RH}{100\%} = \frac{e}{e_s}, \quad (4)$$

where relative humidity RH was measured from the HMP45C and radiosonde. For vertical profiles of q from Eq. (2), pressure was determined from the radiosonde at each level. Pressure at the towers did not drastically change throughout the burn time period; therefore, ambient pressure was used for q at the towers.

Limitations in these calculations concern the definition of fully saturated air. If combustion released moisture at fire front passage completely saturates the surrounding environment, then e_s must be used in place of e in Eq. (2). This results in a quantity for q_s , or the saturated mixing ratio. For these fire environments under analysis in this paper, the assumption remains that the air was not fully saturated.

b. Radiosonde Description

The radiosonde used during the experiments was a Graw, Inc., DFM-06 with a GS-H portable, handheld receiver system. The sonde weighs less than 100 g, and it is the smallest radiosonde available. It measures air temperature with a thermistor and a relative humidity capacitor, and Global Positioning System (GPS) which calculates height and atmospheric pressure and calculates wind speed and wind direction. Measurements are typically obtained from the surface to $\sim 12\,000$ m AGL with data measurement and processing on timescales of 1 s. One unique feature of the Graw radiosonde is that it does not need to be re-calibrated before the sounding is initialized

and is powered with an environmentally friendly dry lithium battery, which eliminates bulk and weight that is associated with other radiosondes.

Radiosonde temperature and relative humidity sensors were tested in hot and cold baths to determine sensor response times, which required calculating a time constant for each test. Temperature sensor time constants, defined as the ratio,

$$\frac{\Delta T_i}{e} = \frac{T(t) - T_e}{T_i - T_e}, \quad (5)$$

are shown in the Appendix (Fig. A.1). Change in initial temperature, ΔT_i is based on the comparison of differences of the temperature at any time $T(t)$ and the initial temperature T_i to the equilibrium temperature T_e . Relative humidity sensor time constants, also in the Appendix (Fig. A.2), follow the same equation with T replaced by RH . Tests were performed for both sensors in the following baths: cold to ambient, ambient to cold, hot to ambient, and ambient to hot. Response time, τ , is the time at which each sensor reached 36.8% of the equilibrium temperature or relative humidity. Table 2 shows the results of τ corresponding to the various baths. On average, the thermistor reacts quicker than the relative humidity capacitor, with an equilibrium temperature at about 2.7 s and the equilibrium relative humidity at about 2.9 s. Response times for both sensors are longer for the cold baths than the hot baths. Hot to ambient and ambient to hot baths respond between 0.7-2.6 s for both sensors, with an average relative humidity capacitor and thermistor response times in a hot environment of 2.0 s and 2.2 s, respectively. As a result, the sensor can reasonably capture the rapid changes as it moves from ambient air to the smoke plume and back to ambient air.

Table 2. Sensor Response Time Tests: Radiosonde sensor response times in cold and hot baths.

Bath	Thermistor Response Time (s)	Relative Humidity Capacitor Response Time (s)
Cold to Ambient	4.7	1.8
Ambient to Cold	1.6	6.1
Hot to Ambient	2.1	0.7
Ambient to Hot	2.2	2.6

c. Experiments

i) R_xFEmEx at Ichauway

The Joseph W. Jones Ecological Research Center at Ichauway is located in southwestern Georgia, centered at 31°13'17"N, 84°28'50"W (Figs. 1 and 2) and consists of 30 000 acres largely dominated by a longleaf pine (*Pinus palustris*) ecosystem. Prescribed fire is required to maintain forest strength and biodiversity. Maintaining forest health is important for Ichauway, since it is used by the elite of society as a Bobwhite quail (*Colinus virginianus*) hunting ground. Conservation staff at the research center assemble a small fire crew to burn ~ 12 000 acres annually. During R_xFEmEx, fire crews lit the prescribed burns with drip torches attached to 4 x 4 all terrain vehicles (ATVs). First, black lining procedures are performed along burn unit perimeters to contain and maintain control of the fire. Then the fire crew light small sections at the downwind edge of the burn unit and allow winds and fuel to drive the fire only short distances. The path of the fire front opposes the direction of the wind and it is therefore, considered a backing fire.

R_xFEmEx Summer was conducted from 15-17 July 2008, in which ~ 350 acres were burned in three plots of land. Weather balloons were launched before black lining

procedures to capture ambient environmental soundings, then after ignition one to two balloons were launched when large smoke plumes had developed. Balloons were specifically launched downwind of the fire and carefully released so vertical ascent and winds would carry balloons through smoke plumes. Each burn also included an interior tower and a downwind tripod with meteorological and air quality instrumentation.

Fig. 1. Joseph W. Jones Ecological Research Center: Location of Joseph W. Jones Ecological Research Center at Ichauway, Georgia.

RxFEmEx Winter was conducted from 12-14 January 2009, where ~ 560 acres were burned in three plots of land under cooler and drier conditions. One addition to the experiment was an ambient afternoon sounding was obtained after the burn was complete and during the smoldering phase. Three meteorological towers were placed surrounding the designated burn units five days prior to burning to obtain ambient surface conditions. As in RxFEmEx Summer, 10 m interior towers and downwind tripods were set up for each burn and were equipped with meteorological and air quality instruments. Data

obtained from RxFemEx Summer and Winter towers and radiosondes will be presented and analyzed in the Results section.

Fig. 2. Ichauway Land Cover: Land cover and satellite composite of Ichauway, the hatched area represents Ichauway land with burn plots colored in green.

ii) Grant Park

Joseph D. Grant County Park (GP) is the largest park in Santa Clara County of California with 9 560 acres of grasslands shaded by a combination of Valley Oak (*Quercus lobata*), California Black Oak (*Quercus kelloggii*), Blue Oak (*Quercus*

douglasii), and a scattering of Coast Live Oak (*Quercus agrifolia*). Regular prescribed burns are required approximately every two years to protect the grasslands and oaks from invasive species. Yellow Starthistle (*Centaurea solstitialis*) and European Oat (*Avena sativa*) are invasive species to the natural wiregrass that covers GP (D. Stocks 2008, personal communication). On 7 October 2008, the California Department of Forestry and Fire Protection (Cal Fire) performed a prescribed fire on a 35 acre burn unit in GP (Fig. 3).

Fig. 3. Burn Unit GP : Location of the tower (red dot) and tripod (yellow dot) relative to the burn plots outlined in green at GP on 7 October 2008.

A 6 m tower was equipped with meteorological sensors and placed inside the burn unit. A meteorological tripod was placed downwind to capture background meteorological conditions and particulate matter 2.5. Data used in this study include temperature and relative humidity measured at the interior tower with a Vaisala, Inc., HMP45C located at 2 m AGL. Additionally, ambient morning conditions were obtained by a sounding conducted north of the burn unit.

Another measurement platform used at GP was a RC airplane and will be discussed in the following sub-section. Measured temperature and calculated water vapor mixing ratio captured on the towers and the RC airplane at the GP burn will be presented in the Results section.

iii) RC Airplane

A RC airplane is a cost effective way to measure smoke plume structure during an active fire. Fire-atmosphere interactions are difficult to obtain due to extreme temperatures of a fire that can melt and destroy instruments placed on the towers. A RC airplane is also more efficient than a weather balloon because smoke plume moisture data is collected only once as the balloon ascends through the smoke plume. On the other hand, a RC airplane can be manually controlled to fly in and out of the plume at multiple levels up to ~ 500 m AGL. This is a novel and economical platform because one radiosonde can obtain multiple *in situ* upper-level and near surface smoke plume characteristics.

The RC airplane was a very small model airplane designed by Hobbico. The Hobbico Avistar 40 II MonoKote ARF .40, 59" RC airplane (Fig. 4) was chosen due to

stability and performance during flight. The almost-ready-to-fly advanced trainer is sold partially assembled and made from balsa wood with an outer plastic covering (additional parts and supplies are described in Table 3 for reference).

Fig. 4. RC Airplane: Hobbico Avistar 40.

Table 3. Additional Equipment: Equipment used for RC airplane.

Item	Model
Airplane	Hobbico Avistar 40 II MonoKote ARF .40,59"
Radio	Futaba 4EXA 4-Channel FM Computer/4 S3004 Servos
Gyros	Two GWS Piezo Gyro PG-03
Motor	O.S. 46AX ABL with muffler
Glue	Tower Hobbies Build-It CA+ Glue 2 oz.
Epoxy	Great Planes Pro Epoxy 30-Min Formula 9 oz.
Brushes	Great Planes Epoxy Brushes
Mixing Cups	Great Planes Epoxy Mixing Cups
Propeller	APC 12x4 Sport Propeller
Glow Plugs	O.S. #8 Glow Plug Long Medium Hot
Glow Plug Igniter	Hobbico Glo-Starter Hot Shot 2
Wheels	Two Dave Brown Lite Wheels 4"
Fuel	Power Master Premium Model Engine Fuel 10% Nitro 18% Oil
Fuel Tank	Sullivan Seamless 24 oz.
Fuel Pump	Hangar 9 Manual Fuel Pump
Engine Starter	Sullivan Deluxe Hi-Tork, Hi-RPM 12 volt starter
Receiver Battery	Airtronics Inc. Receiver NiCd Battery (Flat), 4.8 1000mAh

Even though the fuselage, wings, elevator, and rudder were preassembled, the airplane still required ~ 20 h of additional assembly. Wing joints were glued together and placed inside the wings, which were then glued together with a 30-min epoxy. It is of common procedure to keep the wings detached from the fuselage until just prior to flight, which are then secured onto the fuselage with twelve rubber bands. This ensures flexibility upon unintentional ground impact.

The Futaba RC system includes a handheld transmitter with four servos attached to a receiver which establishes communication between the pilot and airplane. The RC servos were mounted in place: one on the wings to control the ailerons, and three in the fuselage for the elevator, rudder, and throttle controls. The rudder and elevator were strengthened with joints similarly to the wing joints and glued onto the fuselage tail. The servos were connected to their respective parts, and the radio trim settings were adjusted to properly control each part. Engine mounting brackets were placed at the front end of the fuselage and the engine was secured to the brackets. The pressure line and fuel line were threaded from the fuel tank, behind the engine, and connected to the exhaust and engine, respectively. After the engine was installed, the propeller and spinner were mounted onto the crankshaft of the engine. The airplane comes with a 12 oz. (354.9 ml) fuel tank and allows for a 30 min flight; however, longer flights were desired so it was replaced with a 24 oz. (709.8 ml) tank.

The airplane kit also includes three 2" (5.08 cm) foam wheels. A small front wheel maintains easier maneuvering; however, the two back wheels were replaced with 4" wheels for safe landing on gravel roads, dirt, or grass. The completed airplane

measures a 1.5 m wingspan and 1.2 m from propeller to rudder. The pilot reviewed the airplane status and assembly prior to the first test flight. It was then decided to strengthen the wings with fiberglass tape and 5 min epoxy to ensure that the wings would not fold when flying through severe turbulence anticipated in the smoke plume.

The radiosonde device is enclosed in polystyrene thermal insulation for protection. It was removed from the encasement to reduce its size and weight, and was mounted inside the left wing of the airplane. The plastic covering was cut away from the balsa wood and the radiosonde was placed in between the structural ribs of the wing (Fig. 5), thus, the strength of the wing was not altered in this process. In order to balance the radiosonde weight, small weights were taped to the outer edge of the opposite wing.

Fig. 5. Radiosonde in RC Airplane: Graw radiosonde installed in left wing of the Hobbico Avistar 40.

Test flight data were analyzed to determine the quality of radiosonde response time and data obtained during flight. Radiosondes traditionally attached to weather balloons ascend slower than the airplane flies, thus, airplane speed at roughly $4\text{--}6\text{ m s}^{-1}$ versus sensor response time was of concern. Figure 6 shows a 3-D plot of temperature and water vapor mixing ratio obtained during the test flight relative to longitude, latitude, and altitude in m AGL. Results indicate that the radiosonde performs well, with cooler and drier conditions aloft.

Timeseries were produced to see how the radiosonde on the RC airplane capture temperature and water vapor mixing ratio with height (Fig. 7). This 10 min test flight shows as the plane ascended to $\sim 500\text{ m}$, temperature increased and water vapor mixing ratio decreased.

Fig. 6. Test Flight: Flight path with temperature (a) and calculated water vapor mixing ratio (b) obtained from test flight.

Fig. 7. Test Flight in 3D: Timeseries of temperature, water vapor mixing ratio, and altitude obtained during the test flight.

iv) *FireFlux*

Fire-atmosphere interactions were captured by Clements et al. (2007) by strategic arrangement of instruments placed on towers in direct path of a fire front during the FireFlux experiment on 23 February 2006, at the Houston Coastal Center. The 43 and 10 m towers will be referred to as main and short towers, respectively. A complete experimental design is shown in Clements et al. (2007). Meteorological instruments used in this study measured wind velocities in three components, temperature, and relative

humidity. An additional weather station was located 100 m upwind of fire perimeter to measure ambient conditions. A tethersonde was placed downwind of the ignition line at the edge of the burn plot to measure vertical temperature, relative humidity, and wind characteristics. Unfortunately, the tethersonde system only captured plume characteristics during pre-fire black lining because fire-induced turbulence in the main plume broke the carabiner that fastened the balloon to the tether line. The system was lost, but moisture enhancement from the black lining was determined.

Campbell Scientific, Inc., temperature and relative humidity probes (CS-500) were mounted on the 43 m tower at 2.5, 10, 20, and 43 m AGL, sampled at 1 Hz and averaged to produce 1 min data. A Vaisala temperature and relative humidity probe (HMP45C) was mounted at 2.5 m on the short tower and obtained 1 min averaged data. In addition to these standard probes, a fast-response Campbell Scientific Krypton Hygrometer (KH20) was also mounted at 2 m on the short tower and sampled water vapor concentration at 20 Hz. Temperature and moisture enhancement from Fireflux will be presented in the Results section.

3. Results

a. Synoptic Conditions

i) R_xFEmEx Summer

A low pressure system passed over the Great Lakes and moved into New England 12-13 July 2008, the weekend prior to burning. A high pressure system built over the Mississippi Valley and pushed a cold front southward, through the Ohio River Valley and into the Southeast US. The day of the first burn, 14 July 2008, the front extended into northern Georgia and turned stationary. The next day, the front moved over Ichauway and shifted winds from southerly to northeasterly (Fig. 8). This is a usual summertime situation for the Southeast with warm, moist air advected in from the Gulf of Mexico, which often triggers scattered afternoon thunderstorms.

A weather balloon with an attached radiosonde was launched before ignition to obtain ambient background conditions (Fig. 9). The sounding shows surface temperatures were near 25°C, with moist surface conditions and dry air aloft. Wind speed and direction were driven by synoptic scale flow, thus, the weather balloon captured northeasterly surface winds at 5 m s⁻¹, which veered to northerly aloft. Northeasterly winds were a necessity for burn unit S1 due to its location on a northeastern edge of Ichauway bordered by a state highway along the northern edge (Fig. 10). If fire crew were to lose control of the fire, winds would keep fire on Ichauway land.

Fig. 8. R_xFEmEx Summer Weather Conditions: Surface pressure on 15 July 2008.

The stationary front hovered over southern Georgia and northern Florida for the next few days, thus, Ichauway continued to see a north-northeasterly wind. Burn unit S2 also required a northeasterly wind due to a nearby county highway along the northern edge (Fig. 11). Dangerous highway conditions can result when atmospheric stability is too strong, which causes smoke plumes to stay near the surface, instead of mixing out into the free atmosphere. On 17 July 2009, the stationary front weakened and moved eastward, but continued to bring northeasterly winds to Ichauway. Burn unit S3 was not on an outside edge of Ichauway, so wind direction was not of major concern to the fire crew, but was important for downwind tripod placement (Fig. 12). Table 4 shows

archived data of meteorological surface conditions from the National Weather Service (NWS) at Albany, Georgia for each day during R_xFEmEx Summer.

Fig. 9. Atmospheric Profiles for S1, S2, and S3: Ambient conditions of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) water vapor mixing ratio obtained from a radiosonde launched before ignition during R_xFEmEx Summer, all times in EST. Colors correspond to sequential days: 15 July 2008 (black), 16 July 2008 (red), 17 July 2008 (blue).

Table 4. R_xFEmEx Summer Weather: Meteorological conditions at Albany, GA, during R_xFEmEx Summer.

Date	High T (°C)	Low T (°C)	Average RH (%)	Average Wind Speed (m s ⁻¹)	Average Wind Direction (deg)
7/15/08	32	22	76	2.5	70
7/16/08	33	21	60	4.1	45
7/17/08	33	21	58	5.1	30

Fig. 10. Burn Unit S1: Burn unit S1 ~ 200 acres at Ichauway, GA on 15 July 2008. Numbers represent order of balloon launches.

Fig. 11. Burn Unit S2: Burn unit S2 ~ 100 acres at Ichauway, GA on 16 July 2008. Numbers represent order of balloon launches.

Fig. 12. Burn Unit S3: Burn unit S3 ~ 50 acres at Ichauway, GA on 17 July 2008. Numbers represent order of balloon launches and tripod locations.

ii) R_xFEmEx Winter

A low pressure system moved off the Central Rockies and into the Plains prior to burning on 10-11 Jan 2009. This pushed a cold front and trough through the Southeast, and high pressure quickly built in behind the front (Fig. 13) and brought northwesterly winds to Ichauway on 11 July 2009. Meanwhile, a small upper-level shortwave moved in from the Gulf of Mexico and created a more northeasterly wind component and made for tricky forecasts. The low pressure system pushed into the Great Lakes, the shortwave quickly passed, and north-northwesterly winds returned and persisted for the next few days. Weather balloons were launched every morning before ignition. Figure 14 shows ambient morning conditions for all of R_xFEmEx Winter. This was necessary to obtain

local mesoscale conditions to determine where to place downwind tripods each burn day.

The intermittent data for W3 is plotted as the blue profile (Fig. 14), due to poor communication between the radio and receiver which occurred immediately after launch.

Fig. 13. R_xFEmEx Winter Weather Conditions: Surface pressure on 12 January 2009.

A northerly wind component was required for burn unit W1 because a state highway borders the unit along its northern edge (Fig. 15), thus, a northerly wind eliminates any highway visibility concerns. As forecasted, winds varied from northeasterly to northwesterly and it was hard to decide which plot to burn next. Any westerly wind component was required for W3, thus, with winds predicted to vary from 290° to 330°, W2 was chosen due to a highway located on its northwestern edge (Fig. 16).

Fig. 14. Atmospheric Profiles for W1, W2, and W3: Ambient conditions of (a) temperature (solid) dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) water vapor mixing ratio obtained from a radiosonde before ignition during R_xFEmEx Winter, all times in EST. Colors correspond to sequential days: 12 Jan 2009 (black), 13 Jan 2009 (red), 14 Jan 2009 (blue).

Table 5. R_xFEmEx Winter Weather: Meteorological conditions at Albany, GA, during R_xFEmEx Winter.

Date	High T (°C)	Low T (°C)	Average RH (%)	Average Wind Speed (m s ⁻¹)	Average Wind Direction (deg)
1/12/09	12	5.5	64	2.0	30
1/13/09	15	4	67	1.5	300
1/14/09	13	-1	58	3.6	280

Fig. 15. Burn Unit W1: Burn unit W1 ~ 240 acres at Ichauway, GA on 12 January 2009. Numbers represent order of balloon launches.

Due to failed communication between the GPS unit on the radiosonde and the radio receiver and satellites, balloon launches were canceled for W3. Winds performed as predicted and remained from the west-northwest on 14 Jan 2009 and the downwind tripod was placed accordingly (Fig. 17). Table 5 shows archived data of meteorological surface conditions from NWS at Albany, Georgia for each day during R_xFEmEx Winter.

Fig. 16. Burn Unit W2: Burn unit W2 ~ 130 acres at Ichauway, GA on 13 January 2009. Numbers represent order of balloon launches

Fig. 17. Burn Unit W3: Burn unit W3 ~ 130 acres at Ichauway, GA on 14 January 2009.

iii) Grant Park

A ridge of high pressure was situated over southern California while a low pressure system off the coast of the Pacific Northwest pushed a cold front over northern California (Fig. 18). This situation brought northerly winds to the San Francisco Bay Area. Oakland Airport, located 48 miles north of Grant Park, reported west-northwesterly winds varying from $2\text{--}6\text{ m s}^{-1}$, with gusts up to 9 m s^{-1} . Oakland reached a high of 25.5°C with a daily average relative humidity of 69%. A sounding from Oakland Airport obtained at 0500 PDT (= 1200UTC) shows moist surface conditions with dry air aloft (Fig. 19). The 1700 PDT sounding from Oakland Airport shows surface conditions dried out throughout the day. These synoptic conditions were expected to bring a northerly or northwesterly wind component to Grant Park; however, complex terrain plays an important role in determining small scale winds, thus, local meteorological conditions were measured onsite with a radiosonde and a downwind tripod. A radiosonde was launched onsite at 0810 PDT north of the burn unit in Grant Park (Fig. 20) to obtain ambient morning conditions. Conditions at Grant Park were similar to the 1700 PDT-Oakland sounding, with drier surface conditions. Surface winds in Stockman's field were from the north and less than 5 m s^{-1} .

Fig. 18. GP Weather Conditions: Mean sea level pressure on 7 October, 2008.

Fig. 19. Regional Atmospheric Profile on GP: Oakland sounding on 7 October 2008.

Fig. 20. Atmospheric Profile on GP: Temperature(a) (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) water vapor mixing ratio obtained from a radiosonde launched at 0813 PDT in Grant Park.

A meteorological tripod, intended to capture downwind characteristics of the smoke plume, was placed to the southeast of the burn plot due to forecasted northwesterly winds (Fig. 21). At ignition ~ 1125 PDT, Fig. 21 shows valley winds near the burn plot were from the northeast. Surface winds switch to a southerly component around 1250 PDT, and remained from the south for the duration of the burn. This indicates when regional conditions seem to defeat the complex mesoscale valley induced southerly flow.

Fig. 21. GP Tripod: Wind speed (red) and direction (+) data collected at the tripod and averaged to 5 min. Local h is in PDT.

b. Interior Towers

Interior towers were placed within each burn unit to capture meteorological, turbulence, and air quality measurements of the fire front. Temperature and relative humidity measurements were obtained from a HMP45C and Type-T fine-wire thermocouples which measure temperature at a higher rate of 1 Hz. These sensors were used for all prescribed burns during R_xFEMEx at Ichauway, Georgia; GP in Santa Clara County, California; as well as FF in Houston, Texas. The burn method used was backing fires, with a head fire performed near the tower. Ignition crews lit the fuels at least 100 m

upwind from the tower in attempt to simulate a natural, head fire behavior. With a timeseries of temperature and water vapor mixing ratio, the exact time of fire front passage can be determined, and the measurement of moisture fluctuations from the plume and fire front.

High sensor response time and accuracy are essential in capturing the plume temperature structure due to fast moving fire fronts. The two sensors were used simultaneously because they have different response times. The HMP45C has a slower response time than the thermocouples used (Fig. 22). Response times for the HMP45C were verified through personal communication with the engineers at Vaisala, Inc. The HMP45C was designed as a humidity capacitor to be paired with a thermocouple. This is because the relative humidity sensor samples every 15 s, but the temperature sensor responds much slower, every 15 min. As a result, temperature obtained from the HMP45C lagged the thermocouple temperature by ~ 2-5 min. Figure 22 shows the thermocouple and HMP45C temperatures as well as the water vapor mixing ratio calculated from the HMP45C. The spike on the high-frequency thermocouple time series signifies fire front passage, while the increase in HMP45C temperature occurs ~ 3 s later. Due to this sensor lag, it was of interest to use the thermocouple temperature to calculate water vapor mixing ratio. The thermocouple; however, reached unrealistic temperatures and maxed out the sensor, which allowed for unrealistic values of water vapor mixing ratio.

The relative humidity sensor immediately captures increased moisture within the smoke plume, while the temperature sensor on the same instrument peaks after the plume

passes. Achtemeier (2006) was first to couple these instruments together and noticed a lag on the same order of magnitude as seen here, ranging within 2-5 min (Fig. 23). The suggested use for the HMP45C is within a temperature range of -40 to 60°C and is not intended for extreme temperatures, thus, it is not ideal for capturing hot air associated with fire fronts. As a result, this temperature lag affects the calculated water vapor mixing ratio. As the sensor slowly moves towards the high temperatures of the plume air, it forces the relative humidity sensor to drop below pre-fire conditions when the sensor is out of the smoke. This allows for an erroneously low relative humidity after fire front passage.

Fig. 22. S1 Interior Tower: Timeseries of temperature obtained from (a) HMP45C and thermocouple, (b) water vapor mixing ratio calculated from HMP45C during S1.

Fig. 23. Sensor Comparison: A schematic showing how the coupling of the slow-response temperatures sensor (a) to the fast-response moisture sensor (b) in the Vaisala instrument impact relative humidity measurements of smoke. Solid and dashed lines represent sensor and actual smoke conditions, respectively (Adapted from Achtemeier 2006).

Achtemeier (2006) corrected this sensor lag by relating the slow-sensor temperature, T_S (HMP45C) to a base-line temperature T_B of the thermocouple with the equation:

$$T_S^t = T_S^{t-1} + \mathcal{C} \left[\frac{1}{K+1} \sum_{k=1}^K T_B^{t-k} - T_S^{t-1} \right] \quad . \quad (6)$$

This estimates a new temperature that corresponds to the 5 s relative humidity sensor reading by adding the last and previous base-line temperatures. A corrected temperature is produced with two adjustable parameters: an amplitude factor, $\mathcal{C}$, and a lag index, K .

Achtemeier (2006) found the most realistic temperature with lowest variance occurred with $K = 2$ and $\mathcal{C} = 0.035$. These parameters have been tested for the timeseries produced for R_xFEmEx, GP, and FF. Figure 24 shows S1 under the $\mathcal{C}$ chosen by Achtemeier (2006) with varying lag times. A more extreme value of $\mathcal{C}$, not used by Achtemeier (2006), where $\mathcal{C} = 0.5$, was also investigated (Fig. 25). These figures show that as K varies, the spike in temperature does not greatly vary. The use of $K = 2$ used by Achtemeier (2006) is therefore a reasonable lag time.

Fig. 24. Sensor Sensitivity Test 1: Panel (a) shows thermocouple (black), HMP45C (blue), and corrected HMP45C temperatures for S1 with $\mathcal{C} = 0.035$ and $K = 2$ (dashed blue), $K = 3$ (cyan), and $K = 4$ (magenta). Panel (b) shows water vapor mixing ratio for S1 calculated from the HMP45C (blue) and corrected temperatures with $\mathcal{C} = 0.035$ and $K = 2$ (dashed blue), $K = 3$ (cyan), and $K = 4$ (magenta).

Fig. 25. Sensor Sensitivity Test 2: Panel (a) shows thermocouple (black), HMP45C (blue), and corrected HMP45C temperatures for S1 with $C = 0.5$ and $K = 2$ (dashed blue), $K = 3$ (cyan), and $K = 4$ (magenta). Panel (b) shows water vapor mixing ratio for S1 calculated from the HMP45C (blue) and corrected temperatures with $C = 0.5$ and $K = 2$ (dashed blue), $K = 3$ (cyan), and $K = 4$ (magenta).

Values of C used by Achtemeier (2006); however, do not greatly alter the slow-response time of the temperature measurement. Figure 26 shows how C varies with K held at 2. The desired value of C resembles the characteristics of the thermocouple temperature, but also results in a realistic water vapor mixing ratio. For S1 (Fig. 26) when $C = 0.035$ the water vapor mixing ratio remains as low as that calculated from the original temperature; however, when $C = 0.4$, the water vapor mixing ratio reaches 70 g kg^{-1} , a magnitude on the order of 2.3 times greater than that calculated from the original

temperature. When $C = 0.2$, the temperature starts to resemble the thermocouple temperature, and water vapor mixing ratio reaches a reasonable value with a maximum around 40 g kg^{-1} . From these results, an amplitude factor of $C = 0.2$ and a lag factor of $K = 2$ have been applied to data obtained from during the R_xFEmEx, GP, and FF experiments. These will be presented in the following sub-sections.

Fig. 26. Sensor Sensitivity Test 3: Panel (a) shows thermocouple (black), HMP45C (blue), and corrected HMP45C temperatures for S1 with $K = 2$ and $C = 0.035$ (dashed blue), $C = 0.1$ (red), $C = 0.2$ (cyan), $C = 0.3$ (magenta), and $C = 0.4$ (green). Panel (b) shows water vapor mixing ratio for S1 calculated from the HMP45C (blue) and corrected temperatures with $K = 2$ and $C = 0.035$ (dashed blue), $C = 0.1$ (red), $C = 0.2$ (cyan), $C = 0.3$ (magenta), and $C = 0.4$ (green).

i) R_xFEmEx

R_xFEmEx provided an extensive data set for understanding fire-atmosphere interactions as well as seasonal differences, since three burns were conducted under summer conditions and another three under winter conditions. A timeseries of thermocouple temperature and water vapor mixing ratio calculated from the original HMP45C for all R_xFEmEx burns are shown on one figure to provide a general idea of seasonal variations between summer and winter burn conditions (Fig. 27). The differences in ambient conditions from summer to winter are clear, as winter temperatures are on the order of 10-15°C cooler than summer, with ~ 10 g kg⁻¹ more moisture in the summer. Fire fronts passed each tower at each temperature spike, which is shadowed by a similarly sharp increase in water vapor mixing ratio. Water vapor mixing ratio increased more in summer fires than in winter fires on the order of 3-10 g kg⁻¹ and 2-5 g kg⁻¹, respectively. This may be due to different ambient conditions between summer and winter such as drier atmospheric conditions in the winter allowing for drier fuels and higher intensity burns.

Temperature and water vapor mixing ratio for the HMP56C were corrected and are shown in a timeseries of each interior tower from each burn. This provides a detailed analysis of moisture released at fire front and the seasonal differences between Summer and Winter. Typically, the HMP45C was placed between two thermocouples at 2 and 4 m so thermocouple temperatures were averaged to determine an estimate at the HMP45C height. R_xFEmEx Summer was conducted from 15-17 July 2008. Figure 28 shows average thermocouple temperature, HMP45C temperature, and corrected HMP45C

temperature. Water vapor mixing ratio calculated from the HMP45C and the corrected temperatures for S1 are also shown in a timeseries with wind speed and direction (Fig. 28).

Fig. 27. All R_xFEmEx Towers: Timeseries of (a) temperature and (b) calculated water vapor mixing ratio for six R_xFEmEx burns.

Fig. 28. S1 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from S1.

The sharp increase in thermocouple temperature shows fire front passage occurred at roughly 1245 EST (= 1745 UTC) and jumped from 30°C to over 120°C. Water vapor mixing ratio calculated from the corrected HMP45C temperature seems to take a sudden jump from ~ 12.5 to 43.5 g kg^{-1} at the fire front. After the fire front passed, thermocouple temperature slowly recovered to ambient, while water vapor mixing ratio significantly decreased below ambient conditions to 9.4 g kg^{-1} for ~ 5 min before it returned to, pre-fire conditions. Dynamics at fire front passage can be seen in wind speed and direction data captured by an RM Young propeller anemometer. The fire front at S1 caused winds

to shift from northerly to a more southerly component and strengthened by $\sim 1\text{-}2\text{ m s}^{-1}$. Wind shifts associated with the dynamic fire front may have been convectively strengthened by latent heat released from the smoke plume induced moisture increase.

A timeseries produced for S2 shows an interesting double fire front structure (Fig. 29). Averaged thermocouple temperature data show pre-fire temperature was near 30°C and first jumped to 55°C at $\sim 1035\text{ EST}$. Then it rapidly decreased before a gradual increase that lasted $\sim 20\text{ min}$. Stronger winds were associated with the first fire front, while weaker winds were associated with the second. Northeasterly winds; however, shifted to northwesterly during the second plume, which may have redirected the fire front and warm smoke plume back toward the tower and caused this double plume structure. Corrected water vapor mixing ratio took a similar trend with two peaks and increased from pre-fire near 12.6 to 13.5 g kg^{-1} at the fire. It then dropped below ambient to 11.2 g kg^{-1} , increased again to 15.1 g kg^{-1} , and remained at that level for $\sim 20\text{ min}$.

Timeseries of data obtained from S3 (Fig. 30) shows more similarities to S1 than S2 with one drastic temperature spike, which implies the fire front passed the tower once. Ambient average thermocouple temperature varied around 30°C , increased to nearly 200°C at the fire front, then returned to pre-fire conditions within 10 min . Corrected water vapor mixing ratio also increased at $\sim 0910\text{ EST}$. Pre-fire relative humidity was slightly higher than S1 and S2 because this burn occurred earlier in the day when relative humidity is highest.

Fig. 29. S2 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from S2.

Summer relative humidity in the Southeastern US often peaks overnight and gradually decreases throughout the day. Morning conditions were 14.3 g kg^{-1} and then decreased to 11.3 g kg^{-1} before the fire front reached the tower. As the fire passed the tower, water vapor mixing ratio reached 28.4 g kg^{-1} , then consistently decreased and remained near 12.2 g kg^{-1} . Less ambient moisture in the afternoon signifies the observed drying throughout the day was not an effect of the prescribed fire, but a natural

occurrence of daytime heating mixing up the moist air that accumulated at the surface overnight.

Fig. 30. S3 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from S3.

Three burns were conducted for R_xFEMEx Winter from 12-14 January 2009, and data were analyzed similar to R_xFEMEx Summer. A timeseries of averaged thermocouple temperature from W1 (Fig. 31) shows pre-fire conditions near 10°C with a maximum around 60°C at the fire front passage just before at 1230 EST. Pre-fire water vapor mixing ratio calculated from the corrected HMP45C proves to be much lower than

summer burns. Lower ambient relative humidities were expected due to drier winter conditions in the Southeastern US. Figure 31 shows pre-fire water vapor mixing ratio calculated from the corrected HMP45C increased from 2.9 to 8.6 g kg⁻¹ at the fire front. It is of interest to note that water vapor mixing ratio decreased to ambient within 10 min without dropping below ambient, pre-fire conditions. This decrease was seen in all R_xFEmEx Summer burns and may be due to greater background environmental moisture. Wind direction data obtained from the RM Young propeller anemometer during W1 showed inaccuracies, so wind speed and direction measured in u, v, and w components at 10 Hz were obtained from a RM Young sonic anemometer. Winds remained north-northwesterly during W1, but increased by ~ 1.0-1.5 m s⁻¹ at the fire front. Increased moisture found in the smoke plume may have induced these stronger winds near the fire and increased the associated convective dynamics.

A similar analysis was conducted for W2 (Fig. 32) and shows analogous fire front structure to that seen in W1. Ambient average thermocouple temperature at ~ 15°C drastically increased to near 100°C when fire front passage occurred at ~ 1225 EST. Water vapor mixing ratios calculated from the corrected HMP45C increased from an ambient level of 3.8 to 12.2 g kg⁻¹ upon fire front passage. Both temperature and water vapor mixing ratio returned to ambient within 5 min of fire front passage. Again, water vapor mixing ratio did not drop below ambient during this winter burn. Morning pre-fire winds were strong and remained north-northwesterly, which shifted to a more northerly component at the fire front. If this were a fire-induced wind shift, winds would have returned to northwesterly after the fire front passage. This wind shift may be the large-

scale effects of a cold front that passed through the region during W2 because the northeasterly and weaker winds do not resemble pre-fire conditions.

Fig. 31. W1 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from W1.

Fig. 32. W2 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from W2.

Results from W3 take an interesting structure with two temperature spikes that imply two fire fronts (Fig. 33). Pre-fire temperature obtained from the averaged thermocouple data was $\sim 10^{\circ}\text{C}$ and increased to near 60°C upon fire front passage at ~ 1400 EST. Temperature shortly returned to ambient then must have captured another fire front at ~ 1405 EST where a more drastic temperature spike occurred and reached 100°C . Ambient water vapor mixing ratio varied around 1.8 g kg^{-1} and increased to 3.5 g kg^{-1} at the first fire front, then it remained above ambient for ~ 4 min before the second fire front where it reached 9.0 g kg^{-1} . Corrected water vapor mixing ratio and temperature returned

to ambient within 2 min after fire front passage and did not drop below pre-fire conditions. These temperature and moisture spikes are both seen in wind speed and direction data. Pre-fire winds were northwesterly and shifted to northerly when the fire was at the tower. Wind speeds decreased prior to the first fire front and increased by 1-2 m s^{-1} at the second fire front. Approximately 20 min later, and well after the effects of the fire front should be seen, a drastic wind shift and decrease in wind speed occurred. Heat released at the fire front may have had a localized forcing on winds inside the smoke plume, and the moisture released may have enhanced buoyancy to additionally alter convective dynamics at the fire front.

Fig. 33. W3 Tower: Timeseries of (a) thermocouple (black), HMP45C (blue), and corrected temperatures (red), (b) water vapor mixing ratio calculated from HMP45C (blue) and corrected (red), and (c) wind speed and direction from W3.

ii) Grant Park

Data from GP (Fig. 34) was collected and analyzed similarly to R_xFEmEx. The spike in temperature is greater for the thermocouple than for the HMP45C which is again a result of the slower response time of the HMP45C temperature sensor. Note that a 6°C offset between sensors is found before and after the fire front, as was seen in the R_xFEmEx data. Thermocouple temperature increased to roughly 60°C upon fire front passage at ~ 1245 PDT, while the HMP45C temperature reached 35°C with no significant lag present. The corrected HMP45C temperature resembles the thermocouple temperature reaching a maximum at the same time with a slightly higher value than the original HMP45C temperature. Each temperature returned to ambient within 15 min of fire front passage. Corrected water vapor mixing ratio increased from ambient at 5.5 g kg⁻¹ to ~ 8.9 g kg⁻¹ at the fire front. Water vapor mixing ratio never returned to ambient after the fire front passed, which suggests that a new air mass moved into GP. Wind speed and direction data obtained by an Applied Technologies, Inc. sonic anemometer show a drastic wind shift to northerly at ~1240 PDT, and an increase to 4 m s⁻¹ occurred after the fire passed the tower. Observations and photography data prove that the wind shift was strong enough to form a fire whirl at the fire line, ~ 100 m before the fire front reached the tower. This northerly wind component implies that the marine layer moved down the valley from the San Francisco Bay and explains higher moisture levels after the burn.

Fig. 34. GP Tower: Timeseries of (a) 1 min averaged 2m thermocouple (black), HMP45C (blue), and corrected (red) temperature, (b) calculated water vapor mixing ratio from 1 min averaged thermocouple (black), HMP45C (blue), and corrected (blue) temperature, and (c) wind speed and direction sampled at 10 Hz from GP.

iii) FireFlux

Temperature and calculated water vapor mixing ratio obtained from Fireflux were processed differently than R_xFEmEx and GP due to a lack of thermocouple data. The water vapor mixing ratio correction following Achtemeier (2006) was not performed on these datasets because different sensors were utilized during this experiment. Campbell Scientific (CS-500) temperature and relative humidity probes were placed at three levels on the main tower: 2, 10, and 20 m. This provides a sense of how temperature and

water vapor mixing ratio change with height at the fire front and in the smoke plume (Fig. 35).

Fig. 35. FF Main Tower: Timeseries of (a) temperature and (b) water vapor mixing ratio obtained at 2, 10, and 20 m from main tower at FF.

Initially, a sensor offset is seen with the 2 m sensor reading 2°C higher than the 10 and 20 m sensors. All drastically increase at ~ 1245 CST (= 1845 UTC) when the fire front passed the tower. Higher temperatures were found near the surface, with 37°C at 2 m, 34°C at 10 m, and 30°C at 20 m. All sensors returned to ambient within 6 min. This shows a vertical temperature gradient was captured, with warmer conditions at lower levels and closer to the flames, while cooler ambient air mixed into the smoke plume at higher levels. In a timeseries of water vapor mixing ratio, a vertical gradient in moisture

at the fire front can be seen. Ambient conditions were near 8 g kg^{-1} , but upon fire front passage, plume characteristics reached 10.1 g kg^{-1} at 2 m, 11.6 g kg^{-1} at 10 m, and 8.5 g kg^{-1} at 20 m. Higher moisture found at 10 m signifies the highest smoke concentration. Less moisture enhancement at 2 m suggests dry ambient air is mixed into the smoke plume at low levels to feed the fire, while less moisture enhancement at 20 m is due to entrainment of cooler and drier ambient air mixing into the smoke plume.

Li-Cor 7500 open path gas analyzers were also placed on the main tower at 10 and 28 m. Temperature and relative humidity data obtained from these sensors were used to calculate water vapor mixing ratio (Fig. 36). There seems to be a pre-fire offset between the two instruments as 28 m sensor shows ambient conditions were $\sim 10 \text{ g kg}^{-1}$ and 8 g kg^{-1} at 10 m. Both sensors increased as the plume approached, and reached a maximum of 13.7 g kg^{-1} at 10 m and 12.1 g kg^{-1} at 28 m. The Li-Cor 7500 data show similar results found by the CS-500 with more moisture enhancement 10 m, 6.2 g kg^{-1} , than 2.1 g kg^{-1} at 28 m. At both levels, water vapor mixing ratio dips below ambient after fire front passage and return to an ambient level of $\sim 9.0 \text{ g kg}^{-1}$ within 2 min, but drastically drops by 2.0 g kg^{-1} at 28 m (Fig. 36). Interestingly, both sensors measure closer values post-fire than pre-fire. This could be due to soot or dust deposited on sensors or because the extreme fire temperatures altered instrument calibration.

Fig. 36. FF Main Tower in High Frequency: Timeseries of 10 and 28 m high frequency water vapor mixing ratio from main tower at FF.

Observed enhanced moisture, Δq_{obs} , is shown in Table 6 to compare to a theoretical model designed by Potter (2003) and altered by Clements et al. (2006) via Eq. (1). There are two columns to represent the value of the layer of the atmosphere affected by the plume: H_M and H_{MAX} , as the average layer of the atmosphere affected by the plume and the maximum layer affected by the plume, respectively. This allows for two different values of smoke plume moisture enhancement: Δq_v and Δq_{vMaxH} , the estimated water vapor mixing ratios using H_M and H_{MAX} , respectively. When increasing the volume of air affected by the plume, smoke plume moisture enhancement consequently decreases.

Table 6. Plume Moisture Summary: Observed versus estimated enhanced plume moisture, and values used in calculation, for all burns. All values of Δq_{obs} , Δq_v , and Δq_{vMaxH} are in units of (g kg⁻¹).

Burn	Δq_{obs}	Δq_v	Δq_v <i>Max H</i>	f (kg m ⁻²)	H_M (m)	H_{MAX} (m)	M (%)	u (m s ⁻¹)	u_f (m s ⁻¹)
S1	10.4								
S1 _{cor}	29.8	3.1	0.5	0.315	30	200	32	1.3	1
S2	3.8								
S2 _{cor}	5.7	3.3	0.5	0.336	30	200	32	1.3	1
S3	7.9								
S3 _{cor}	11.1	2.6	0.4	0.261	30	200	32	1.3	1
W1	3.3								
W1 _{cor}	5.7	2.1	0.6	0.261	30	100	16	1.3	1
W2	4.8								
W2 _{cor}	8.3	2.7	0.2	0.336	30	100	16	1.3	1
W3	4.5								
W3 _{cor}	7.3	2.5	0.2	0.315	30	100	16	1.3	1
GP	2.4								
GP _{cor}	3.7	0.6	0.1	0.112	30	200	28.5	1.5	1
FF2m									
CS-500	2.1	2.0	NA	1.08	30	NA	15	3	1.3
FF10m									
CS-500	3.5	2.0	NA	1.08	30	NA	15	3	1.3
FF20m									
CS-500	1.0	2.0	NA	1.08	30	NA	15	3	1.3
FF10m									
LiCor7500	6.2	2.0	NA	1.08	30	NA	15	3	1.3
FF28m									
LiCor7500	2.1	2.0	NA	1.08	30	NA	15	3	1.3

In summary, temperature and relative humidity obtained on towers in direct passage of fire fronts have been presented from R_xFEmEx Summer and Winter, GP, and FF. Water vapor mixing ratio was calculated and corrected following Achtemeier (2006) to determine plume moisture enhancement. Most important comparisons are the seasonal differences noticed in R_xFEmEx due to identical fuels burned at six different times, with three under each summer and winter conditions. Major differences were identified between summer and winter prescribed burns and it became apparent that prescribed

burns have seasonal characteristics. Ambient surface temperatures were 10-15°C warmer with surface moisture $\sim 10 \text{ g kg}^{-1}$ greater in summer. This is a result of usual summertime warm and humid conditions present in the Southeast US. Upon fire front passage, smoke plume moisture increase was on the order of 3 to 10 g kg^{-1} during summer burns and 3 to 5 g kg^{-1} during winter burns. After applying the correction following Achtemeier (2006), these values increased to 5 to 30 g kg^{-1} and 5 to 9 g kg^{-1} , respectively. On average, corrected temperature increased moisture enhancement by a factor of 1.5 to 2.

These prescribed fires exposed these instruments to environments that exceeded the intended temperature thresholds. Also noted by others, such as Achtemeier (2006) and the Vaisala manufacturer, the temperature sensor on the HMP45C lags the true temperature by 2-5 min. This is because the temperature sensor averages every 15 min and the relative humidity sensor averages every 15 s. The extreme temperatures of the fire well exceeded the manufacturer suggested range between -40 to 60°C.

Tower data was compared to an aerodynamic model from Clements et al. (2006) on enhanced plume moisture. The model seems to underestimate the magnitude of the moisture enhancement in all burns except for the 20 m LiCor-7500 at FF. On the other hand, changes in magnitude calculated by the model are consistent with observations. For example, the greatest observed moisture enhancement for R_xFEmEx Winter occurred during W2 and the least moisture enhancement was during W1. Similarly, the model outputs follow this trend. On the other hand, the model was able to more accurately estimate moisture enhancement during FF, which may be due to the lower moisture levels

observed. Another issue with the model may involve the value of H_M and the smoke plume moisture enhancement compared to the volume of air considered in calculations.

c. Soundings

Radiosonde measurements were obtained during each burn at Ichauway, Georgia. Radiosondes, as described in Chapter 2, were launched every morning before ignition. After black lining and test fires, fire crews ignited the burn unit using backing strip fires. When substantial plumes developed, one to two balloons were launched and ascended directly through smoke plumes. This allowed for a comparison between ambient morning conditions and *in situ* plume measurements. For winter burns, another balloon was launched in the afternoon, well after the smoldering stage, to obtain ambient afternoon environmental conditions.

Vertical profiles from S1 are shown on a four panel plot (Fig. 37) of temperature and dewpoint temperature, wind speed and direction, potential temperature, and water vapor mixing ratio from the surface up to 5000 m AGL. The ambient sounding at 0956 EST shows surface temperature was 24.2°C with a dewpoint temperature of 20.5°C. In-plume soundings show warmer surface temperature due to normal diurnal heating. The 1153 EST and 1246 EST profiles also show a warmer layer between 100-200 m AGL and from the surface up to 400 m AGL, respectively, which signify plume structure. Dewpoint temperatures also increased at these levels by 0.5-1.5°C for each in-plume profile and imply more moisture exists within the smoke plume. Winds at 200 m AGL decreased from ambient at 5 m s⁻¹ to ~ 2.5 m s⁻¹ at 1153 EST, but increased to ~ 6 m s⁻¹ at 1246 EST. This is expected because stronger winds at lower levels usually occur later in

the day as a result of the developed boundary layer. Ambient wind direction remained northeasterly within the boundary layer, but shifted to a more northerly component in the warm layer of the 1153 EST sounding. An opposite wind shift to more easterly, and an increase in velocity to 6 m s^{-1} occurred in the warm plume layer with strong shear to northerly above the boundary layer on the 1246 EST profile. These changes in wind illustrate the effects of the plume on momentum.

Potential temperature was plotted to show stability for each profile and boundary layer evolution. Further analysis of the lowest 2000 m AGL of the fire-atmosphere environment is to follow. Synoptic scale profiles show boundary layer increased from 1000 m AGL at 0956 EST to 1200 m AGL at 1153 EST and to 1400 m AGL at 1246 EST. Above the boundary layer, ambient and plume soundings show similar atmospheric conditions, except for the 1246 EST profile which shows a cool layer in the from 1400 m AGL to 2000 m AGL. This above boundary layer cooling is significant as it is on the order of $\sim 2.5 \text{ K}$. Water vapor mixing ratio increased throughout the day in the boundary layer while ambient and plume conditions agree throughout the free atmosphere.

Sounding data from nearby NWS stations were obtained from Tallahassee, Florida (TLH) and Peachtree City, Georgia (FFC) and are plotted with the ambient profile from S1 (Fig. 38). This was performed to investigate the accuracy of the radiosonde as well as potential temperature and water vapor mixing ratio computations. Atmospheric structure was captured and all ambient conditions are in overall agreement with NWS data for all burns performed. Ambient morning conditions R_xFEmEx , FFC, and TLH are all similar, except surface conditions differ at THL as it is located closer to

the Gulf of Mexico with stronger surface winds and more moisture. Only S1 was compared to TLH and FFC because drastic differences were not found in any of the other burns. The comparison is necessary for S1 to determine whether cooler air aloft was due to advection of a new airmass, or localized effects of the prescribed fire. Cooler air aloft is observed in the TLH afternoon sounding from 1400-2000 m AGL (Fig. 38), but is on the order of 1 K, whereas the 1246 EST plume sounding in Fig. 37 observed a 2.5 K cooling in this layer. Thus, the warming at lower levels may have affected the cooling aloft.

Fig. 37. S1 Radiosondes: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) water vapor mixing ratio obtained from S1.

Fig. 38. Data Verification: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) water vapor mixing ratio obtained from S1, FFC, and TLH all times in EST.

Boundary layer profiles were produced to analyze potential temperature and plume stability and water vapor mixing ratio within the smoke plume from the surface to 2000 m AGL (Fig. 39). Bulk Richardson, Ri , number is used as a stability parameter and is a ratio of buoyancy to shear (Stull 1988). The following form of Ri was used because it accounts for air moisture (Stull 2000) and is given by,

$$Ri = \frac{|g| \cdot \Delta\theta_v \cdot \Delta Z}{T_v \cdot [(\Delta U)^2 + (\Delta V)^2]}, \quad (7)$$

where $\Delta\theta_v$ is change in virtual potential temperature, ΔZ is height, T_v is virtual

temperature, ΔU and ΔV represent changes in horizontal wind velocities, and g represents gravity. Stull (2000) defines the critical Richardson number, $Ri_c = 0.25$. For $Ri < Ri_c$, flow is dynamically unstable and a negative Ri implies statically unstable, while $Ri > Ri_c$ describes dynamically stable flow. Ambient conditions were statically unstable in the lowest layer from the surface to 300 m AGL and became more stable aloft. The 1153 EST sounding shows stability within this lowest layer, with unstable conditions throughout the boundary layer and stable conditions in the free atmosphere. There is one point where $Ri < Ri_c$ that implies a shallow layer of instability near 200 m AGL within the plume. Dynamic instability is observed within the lowest layer of the 1246 EST profile, with similar stable conditions aloft. Instability within the smoke plume implies the buoyancy above the prescribed fire was greater than ambient conditions, as expected.

Figure 39 also shows potential temperature and water vapor mixing ratio. Surface potential temperature increased from 297.1 K at 0956 EST to 299.1 K at 1153 EST and to 301.9 K at 1246 EST. Surface water vapor mixing ratios also increased from 15.4 g kg⁻¹ to 15.9 g kg⁻¹ and to 18.0 g kg⁻¹. The 1136 EST profile was chosen as the S1 plume sounding due to its smoother and more prominent plume structure. The ambient potential temperature and moisture of the 1136 EST profile were obtained by taking the average of each variable below and above the plume signatures. Potential temperature increased from 299.2 to 300.3 K and water vapor mixing ratio increased from 15.9 to 17.1 g kg⁻¹ at 150 m AGL, a plume temperature and moisture enhancement of 1.06 K and 1.2 g kg⁻¹, respectively.

Fig. 39. S1 Boundary Layer Radiosondes: Evolution of soundings of (a) potential temperature, (b) water vapor mixing ratio, and (c) bulk Richardson number obtained from S1. The grey line represents Ri_c .

Plume stability was also determined by calculating $\partial\theta/\partial z$, or change in potential temperature with height, at various levels within each profile. The warm plume layer of the 1136 EST sounding is associated with a $\partial\theta/\partial z = -0.1 \text{ K m}^{-1}$ and implies plume instability. While the 1246 EST profile shows higher temperature in a deeper layer, the exact level of the plume is more difficult to discern. This made it more difficult to determine the plume temperature and moisture enhancement. Averaging the potential temperature and water vapor mixing ratio at the surface with the coolest and driest level at 300 m AGL provided ambient conditions for comparison. Plume temperature and

moisture increased from 300.8 to 303.4 K and 16.5 to 18.9 g kg⁻¹, an enhancement of 2.6 K and 2.5 g kg⁻¹, respectively. The deep plume layer of the 1246 EST profile has multiple layers of potential temperature gradient, but the deepest layer with a more constant stability value exists from 100-300 m AGL on the 1246 EST profile. This layer shows a potential temperature gradient of $\partial\theta/\partial z = -0.2 \text{ K m}^{-1}$ within the plume.

Soundings from S2 were obtained and plotted similarly to S1, but a limited number of radiosondes allowed for only one in-plume sounding (Fig. 40). The ambient surface temperatures were 30.2°C with a dewpoint temperature of 24.0°C, and both decreased to 28.9°C with a dewpoint of 20.7°C at 1023 EST. Cooling throughout the day is not expected; however, greater moisture early in the morning is a result of dew collecting on the surface overnight. Temperature and dewpoint temperature from the 0910 EST profile differ from the 1023 EST profile within the boundary layer, but converge in the free atmosphere. Ambient winds increased with height and veered from northeasterly to more easterly. At 1023 EST, winds remained from the east throughout the boundary layer. Plume structure is signified by a rapid increase in wind speed in the lowest 100 m AGL to 7 m s⁻¹ on the 1023 EST profile, then return to ambient conditions above the boundary layer (Fig. 40). The mixed layer increases from 500 m AGL at 0910 EST to 900 m AGL at 1023 EST, and both show signatures of a residual layer to 1000 and 1500 m AGL, respectively. The latter measurement signifies the boundary layer top. Boundary layer height is expected to increase as the mixed layer deepens throughout the day, but it may have increased more rapidly due to the presence of the fire. Pre-fire surface water vapor mixing ratio at 19.1 g kg⁻¹ rapidly decreases with height, while the

plume profile remains constant at 15.5 g kg^{-1} within the mixed layer. Water vapor mixing ratios in the free atmosphere generally agree up to 5000 m AGL.

During S2, radiosondes were launched downwind of the burn plot in a berry field surrounded by longleaf pine. Due to weak surface winds and a strong stable layer above the smoke plume, smoke was pooled into this berry field and trapped with little dispersion. These smoky surface conditions were noted by onsite observations and may explain the deeper mixed layer in the plume profile.

Fig. 40. S2 Radiosondes: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) calculated water vapor mixing ratio obtained from S2.

Boundary layer profiles of potential temperature, water vapor mixing ratio, and Ri from S2 (Fig. 41) allow for further analysis of plume structure and characteristics. The pre-fire sounding shows an unstable surface layer extending to 400 m AGL below the mixed and residual layers. The depth of the unstable layer on the pre-fire sounding at 0910 EST may not be realistic, as the radiosonde may have interpolated between missing data points. The 1023 EST profile shows that a shallow superadiabatic layer exists near the surface with a mixed layer to 800 m AGL (Fig. 41). Within the lowest 400 m AGL, $Ri < Ri_c$ for both profiles to imply both were dynamically unstable. Surface potential temperature decreased from 302.3 K at 0910 EST to 301.1 K at 1023 EST and surface water vapor mixing ratios decreased from 19.1 to 15.5 g kg⁻¹, respectively. The 1023 EST profile shows potential temperature within the lowest 400 m AGL was 300.3 K, and it decreased to 299.7 K from 500 to 800 m AGL. This suggests the warm smoke plume enhanced mixing, brought warmer air down to the surface, and then returned to ambient in the mixed layer above the smoke plume. Perturbations in temperature and moisture due to the presence of the plume in the lowest layer were determined by averaging each of the variables from the surface to 500 m AGL. These were compared to maximum potential temperature and water vapor mixing ratio within the plume layer. This comparison results in a smoke plume temperature and moisture enhancement of 0.5 K and 0.7 g kg⁻¹, respectively. The mixed layer allows for neutral stability where $\partial\theta/\partial z = 0$ K m⁻¹. Above this layer at 500 m AGL, $\partial\theta/\partial z = -0.005$ K m⁻¹, which implies a shallow unstable layer existed above the smoke plume, or a transition layer from the top of the plume to ambient air.

Fig. 41. S2 Boundary Layer Radiosondes: Evolution of soundings of (a) potential temperature, (b) water vapor mixing ratio, and (c) bulk Richardson number obtained from S2. The grey line represents Ri_c .

Two soundings obtained from S3 were plotted similarly to S1 and S2 (Fig. 42).

Ambient surface temperature and dewpoint temperature at 0756 EST were 25.9 and 21.3°C, respectively. While at 0904 EST the surface warmed to 26.1°C, but dried out to a dewpoint temperature of 19.3°C. Temperature increased on the 0904 EST profile between 50 to 400 m AGL, to signify plume warming. Otherwise, the two profiles roughly agree throughout the free atmosphere. Ambient surface winds were east-northeasterly near 2 m s⁻¹ and remained from the northeast and increased with height throughout the boundary layer. Surface winds at 0904 EST were roughly the same speed as the ambient sounding, but they shifted to a more northerly component and veered to

northeasterly within the boundary layer. Residual layer height did not drastically change during S3 possibly due to an early ignition time and because soundings were launched nearly 1 h apart. The mixed layer grew rapidly during the period, while the boundary layer height remained near 1500 m AGL. Water vapor mixing ratios within the boundary layer varied frequently with height for both profiles, while they agree throughout the free atmosphere.

Fig. 42. S3 Radiosondes: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) calculated water vapor mixing ratio obtained from S3.

Boundary layer profiles of potential temperature, water vapor mixing ratio, and Ri from S3 (Fig. 43) allow for further plume structure investigation. A superadiabatic layer exists in the lowest 50 m AGL on the ambient sounding and remains unstable to 100 m AGL. The remaining stable layer extends to 250 m AGL with the residual layer up to 1500 m AGL, or the top of the mixed layer. This instability can also be seen as $Ri < Ri_c$ within the lowest layer, while the pre-fire environment is stable, or $Ri > Ri_c$, from 200 m AGL and aloft. At 0904 EST the same super adiabatic layer exists within the lowest 25 m AGL with a shallow mixed layer up to 50 m AGL (Fig. 43). There is a deep warm layer above the shallow mixed layer with increased potential temperature from 100 to 300 m AGL. This is the plume layer because it is topped with the ambient mixed 750 m AGL and residual layers up to 1500 m AGL. Throughout the boundary layer on the 0904 EST profile, $Ri < Ri_c$ and implies dynamic instability. There is one point where $Ri > Ri_c$ at 50 m AGL, which is associated with the warm temperature at the bottom of the smoke plume and implies instability is associated with the fire front.

Potential temperature at the surface increased slightly from 298.1 K to 298.4 K, while surface water vapor mixing ratio decreased from 16.1 to 14.2 g kg⁻¹ from the ambient to the 0904 EST soundings, respectively. Perturbations in potential temperature and water vapor mixing ratio within the lowest 300 m AGL were calculated by averaging these variables in the mixed layer from 300 to 700 m AGL. This provided an ambient mixed layer potential temperature of 298.7 K and water vapor mixing ratio of 13.4 g kg⁻¹. Potential temperature increased to 300.6 K while water vapor mixing ratio increased to 15.6 g kg⁻¹ within the warm and moist plume layer. This indicates a plume temperature

and moisture enhancement of 1.9 K and 2.2 g kg⁻¹, respectively. Moreover, the warm plume layer from 100 to 300 m AGL is associated with an unstable layer where $\partial\theta/\partial z = -0.01$ K m⁻¹.

Fig. 43. S3 Boundary Layer Radiosondes: Evolution of soundings of (a) potential temperature, (b) water vapor mixing ratio, and (c) bulk Richardson number obtained from S3. The grey line represents Ri_c .

During winter burns, an extra radiosonde was launched after the smoldering phase of the prescribed burns to provide ambient, post-burn, afternoon conditions. Two ambient soundings and two in-plume soundings are shown in Fig. 44. Ambient morning surface temperature was 9.3°C with a dewpoint temperature of -2.8°C at 1053 EST and in the afternoon warmed to 14.0°C with a dewpoint of 0.2°C at 1433 EST. Surface

temperature increased throughout the day due to normal daytime heating to 12.6°C at 1159 EST and to 11.0°C at 1256 EST. Surface dewpoint temperature; however, decreased throughout the day to 0.2°C by 1433 EST. Environmental moisture in the winter is expected to decrease throughout the day in the Southeastern US, as mixing enhances throughout the day due to diurnal heating.

The 1159 EST balloon was launched on a road inside the burn unit, near the fire front, and within smoky conditions, whereas the 1256 EST balloon was launched in clear air and rose directly into the smoke plume. Thus, much warmer surface conditions were captured on the 1159 EST plume sounding. Pre-fire morning winds were northeasterly near the surface, then shifted to easterly throughout the boundary layer, and to westerly in the free atmosphere. Ambient afternoon winds varied around easterly throughout the entire boundary layer and were weaker than the morning, but also shifted to westerly in the free atmosphere. Figure 44 shows the presence of a strong low-level jet between 25 to 75 m AGL. At 1159 EST, winds remain more easterly in the boundary layer and are westerly aloft; however, the 1256 EST profile shows westerly winds in the lowest layer, then easterly from 100 m AGL and returned to westerly in the free atmosphere. Temperature, dewpoint temperature, and wind speed and direction for ambient and in-plume conditions all show a similar structure throughout the free atmosphere.

Boundary layer depth did not drastically change throughout the day, as seen in the potential temperature plot, while the evolution of the deepening mixed layer will be discussed in the subsequent boundary layer analysis. Boundary layer height increased from morning, pre-fire conditions at 800 m AGL to 1000 m AGL in the afternoon (Fig.

44). Above the boundary layer the 1053 and 1159 EST soundings look similar in structure, while the 1256 and 1433 EST soundings were 5 to 10 K cooler. Meanwhile, water vapor mixing ratio for all four soundings is similar in structure above the boundary layer and varies slightly near the surface due to the presence of the smoke plume.

Ambient water vapor mixing ratio in the Southeastern US is less during the winter than the summer, as it is considered the dry season. The profile evolution shows less moisture enhancement than found in the summer. Morning surface water vapor mixing ratio at 1053 EST is near 3.0 g kg^{-1} and at 3.9 g kg^{-1} in the afternoon at 1433 EST. Greater moisture in the afternoon implies increased moisture was not a small scale effect of the fire, but rather normal daytime atmospheric evolution or advection of a new air mass, possibly brought to the region by the low-level jet.

Profiles of boundary layer potential temperature, water vapor mixing ratio, and Ri (Fig. 45) are shown analogous to summer burns. Surface potential temperature increased from 280.9 K at 1053 EST to 285.6 K at 1433 EST. The pre-fire morning profile shows a deep superadiabatic layer from the surface to 250 m AGL, with a stable boundary layer up to 400 m AGL, and topped by the residual layer from the previous day. The ambient afternoon profile shows a shallower superadiabatic layer from the surface to 200 m AGL. This is due to vertical mixing caused by diurnal heating, which created a deep mixed layer extending up to 700 m AGL. The boundary layer top is difficult to depict in the afternoon post-fire profile because a less prominent residual layer exists above the mixed layer (Fig. 45).

Fig. 44. W1 Radiosondes: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) calculated water vapor mixing ratio obtained from W1.

Two different plume structures are shown in the 1159 and 1256 EST plume profiles in Fig. 45. Since the 1159 EST balloon was launched near the fire front, it captured a stronger surface warming with potential temperature at 284.3 K. The 1256 EST profile depicts the usual plume signature with cooler surface conditions and a warm layer between 50 to 200 m AGL, as it was launched in clear air downwind of the burn unit and ascended through the smoke. Thus, surface potential temperature at 1256 EST was cooler than the previous at 282.6 K. Both plume profiles illustrate the ambient mixed layer above the warm plume layers (Fig. 45). These structures made for a difficult

ambient-to-plume comparison. Perturbations due to the plume were determined by estimating an ambient surface temperature that was found by considering the same superadiabatic environmental structure as ambient conditions and compared to the temperatures on the plume profiles. This provided an ambient potential temperature of 282.9 K at the smoke plume level between 0 to 300 m AGL at 1159 EST and a plume warming of 2.0 K. Ambient potential temperature for the 1246 EST plume profile in the lowest 200 m AGL was taken by averaging surface and mixed layer potential temperature, which then results in an ambient potential temperature of 281.6 K. Since the maximum temperature in the plume reached 284.9K, this allows for a smoke plume warming of 2.9 K.

Figure 45 shows for all soundings, $Ri < Ri_c$ under 500 m AGL, so each are dynamically unstable. It is interesting to note that $Ri < 0$ for one point on the 1159 EST sounding, and implies static instability. The presence of the fire may have supported ambient instability and created a more unstable environment.

Surface water vapor mixing ratio increased throughout the day from 3.0 g kg⁻¹ at 1053 EST to 4.1 g kg⁻¹ at 1159 EST and 3.6 g kg⁻¹ at 1256 EST and to 3.8 g kg⁻¹ at 1433 EST. Ambient surface moisture was roughly estimated by taking the difference between that at 1159 EST and 1433 EST. This allows for a smoke plume moisture enhancement of 0.3 g kg⁻¹ for the 1159 EST plume structure. A moist layer exists on the 1256 EST profile and coincides with the warm plume layer from 50 to 200 m AGL. Perturbation in water vapor mixing ratio due to the smoke plume at this time was calculated similarly to potential temperature, which provides ambient moisture of 3.3 g kg⁻¹ at the plume level

between 0 to 250 m AGL. The plume layer reached 3.7 g kg^{-1} , or a smoke plume moisture enhancement of 0.4 g kg^{-1} at 1256 EST.

As the maximum potential temperature on the 1153 EST sounding was near the surface, stability was calculated from the surface up to the bottom of the mixed layer, from 0 to 300 m AGL, $\partial\theta/\partial z = -0.02 \text{ K m}^{-1}$, but is more likely a result of ambient environmental instability than from the effects of the fire. The deeper warm layer from 100 to 200 m AGL at 1256 EST in Fig. 45 corresponds to $\partial\theta/\partial z = -0.03 \text{ K m}^{-1}$, which implies a strong potential temperature gradient.

Fig. 45. W1 Boundary Layer Radiosondes: Evolution of soundings of (a) potential temperature, (b) water vapor mixing ratio, and (c) bulk Richardson number obtained from W1. The grey line represents Ri_c .

Ambient and plume soundings obtained from W2 resemble those from W1 because four balloon launches captured two ambient profiles and two in-plume profiles (Fig. 46). Ambient morning surface temperature was 9.3°C with a dewpoint temperature of 3.2°C at 1022 EST. By 1443 EST, it had warmed up to 15.4°C, but dried out to a dewpoint temperature of -1.5°C. Similarly to W1, the 1256 EST balloon was launched in smoke free air, downwind from the burn unit and rose into the smoke plume, whereas the 1159 EST balloon was launched in the burn unit near the fire front with high levels of smoke observed at the surface. This is again why the 1159 EST profile is warmer at the surface, at 13.6°C, than 12.2°C at the surface at 1256 EST.

Radio communication was interrupted during the 1443 EST sounding and resulted in lost data in the free atmosphere. The ambient boundary layer structure was captured so the profile is included in analysis. The other profiles agree above the boundary layer, but the 1443 EST profile shows a greater temperature and lower dewpoint temperature than ambient morning conditions throughout the boundary layer. Pre-fire morning winds backed from northerly to northwesterly in the boundary layer and to westerly in the free atmosphere. Post-fire afternoon winds varied around northwesterly near the surface and throughout the boundary layer, and then they returned to pre-fire conditions aloft. Boundary layer wind speeds did not drastically vary over the course of the day, but were much stronger than the other burns. Boundary layer height increased from 700 m AGL at 1022 EST to 900 m AGL at 1159 EST to 1000 m AGL at 1256 EST, to 1200 m AGL at 1443 EST. Unlike W1, water vapor mixing ratio decreased throughout the day, which may be due to cold air advection associated with backing winds. Water vapor mixing

ratios were relatively the same above the boundary layer for all soundings except for the 1443 EST, which may have inaccuracies associated with the intermittent data just prior to lost communication between the radiosonde and receiver.

Fig. 46. W2 Radiosondes: Evolution of soundings of (a) temperature (solid) and dewpoint temperature (dashed), (b) wind speed (solid) and direction ($\diamond$), (c) potential temperature, (d) calculated water vapor mixing ratio obtained from W2.

Figure 47 shows a detailed view of the profiles of boundary layer potential temperature, water vapor mixing ratio, and Ri from the surface to 2000 m AGL to allow for a more thorough boundary layer investigation. Pre-fire surface potential temperature at 1022 EST was 281.4 K with a stable surface layer up to 300 m AGL, and above this altitude, the residual layer extends to the free atmosphere at 700 m AGL. The afternoon

post-fire conditions at 1443 EST show a warm layer below 100 m AGL, which could be a residual effect of localized warming by the fire. Above this warm layer, a weak unstable layer extends to the boundary layer top at 1200 m AGL. At 1159 EST, potential temperature at the surface increased to 285.8 K with an adiabatic layer to 400 m AGL and topped with the ambient residual layer. Potential temperature at 1256 EST was 284.1 K at the surface and increased to 288.5 K at 100 m AGL to signify the warm plume layer (Fig. 47). Above the smoke plume, conditions return to ambient with an adiabatic layer extending to 1000 m AGL. Considering the afternoon post-fire conditions, one would expect a mixed layer or residual layer to exist above the smoke plume.

Perturbations in potential temperature and moisture from the presence of the smoke plume are difficult to discern for the 1159 EST plume profile due to the deep adiabatic layer and additional surface warming by the fire (Fig. 47). Since the two plume profiles were obtained approximately 1 h apart, and the 1256 EST balloon was launched in clear air downwind of the burn unit to ascend through the smoke, the surface potential temperature and water vapor mixing ratios from the 1256 EST profile provided ambient conditions at 1159 EST. This comparison results in a smoke plume temperature and moisture enhancement of 1.7 K and 0.6 g kg^{-1} , respectively for the 1159 plume profile. This adiabatic layer from 0-400 m AGL results in $\partial\theta/\partial z = -0.01 \text{ K m}^{-1}$ and is a deep unstable layer. Averaging surface and 300 m AGL potential temperature and water vapor mixing ratio allowed for ambient conditions in the lowest layer. These estimated ambient conditions were compared to maximum potential temperature and water vapor mixing ratios in the same level. Thus, for the 1256 EST plume sounding, smoke plume

temperature and moisture increased by 3.8 K and 0.8 g kg⁻¹, respectively. This warm plume layer from 100 to 200 m AGL is associated with $\partial\theta/\partial z = -0.01$ K m⁻¹, which implies plume instability.

During W2, $Ri < Ri_c$ for all profiles under 500 m AGL, except for one layer on the 1256 EST sounding. The warm plume structure resulted in $Ri > Ri_c$ for one layer within the plume and implies stable flow, while the other profiles remain dynamically unstable at this level.

Fig. 47. W2 Boundary Layer Radiosondes: Evolution of soundings of (a) potential temperature, (b) water vapor mixing ratio, and (c) bulk Richardson number obtained from W2. The grey line represents Ri_c .

All plume soundings were averaged to determine bulk characteristics of plume structure versus ambient environmental conditions. Summer and winter profiles had to

be averaged separately as there was roughly a 15 K potential temperature difference and 10 g kg^{-1} difference in water vapor mixing ratio (Fig. 48). Each profile shows an increase in potential temperature and water vapor mixing ratio within the lowest 200 m AGL, indicating the smoke plumes. Panels (c) and (d) are averages of summer and winter profiles to show a general profile of smoke plume structure, and show instability within the plume until the ambient mixed layer is reached above the plume, and the free atmosphere at roughly 1000 m AGL.

Fig. 48. All R_xFEmEx Plume Soundings: Plume soundings of (a) potential temperature and (b) water vapor mixing ratio, as well as summer (solid) and winter (dashed) averaged (c) potential temperature and (d) water vapor mixing ratio, all times in EST.

Observed enhanced moisture, Δq_{obs} , obtained from the radiosondes is shown in Table 7 to compare to a theoretical model designed by Potter (2003) and altered by

Clements et al. (2006) via Eq. (1). Again, there are two columns to represent the value of the layer of the atmosphere affected by the plume: H_M and H_{MAX} . This similarly allows for two different values of smoke plume moisture enhancement: Δq_{obs} and $\Delta q_{obsMaxH}$. As seen in the calculations for the tower data, when increasing the volume of air affected by the plume, smoke plume moisture enhancement decreases.

Table 7. Modeled Plume Moisture Summary: Observed versus estimated enhanced plume moisture, and values used in calculation, for all burns. All values of Δq_{obs} , Δq_v , and Δq_{vMaxH} are in units of (g kg^{-1}).

Burn	Δq_{obs}	Δq_v	Δq_{vMaxH}	f (kg m^{-2})	H_M (m)	H_{MAX} (m)	M (%)	u (m s^{-1})	u_f (m s^{-1})
S1	1.1 2.6	3.1	0.5	0.315	30	200	32	1.3	1
S2	0.5	3.3	0.5	0.336	30	200	32	1.3	1
S3	1.9	2.6	0.4	0.261	30	200	32	1.3	1
W1	2.0 2.9	2.1	0.6	0.261	30	100	16	1.3	1
W2	1.7 3.8	2.7	0.2	0.336	30	100	16	1.3	1

In summary, multiple radiosondes were launched during Summer and Winter RxFEmEx to obtain *in situ* plume profiles as well as ambient environmental conditions before and after the burning stage. This allowed for a stability analysis and to determine bulk Richardson number for various layers under, within, and above smoke plumes. For most burns, $Ri < Ri_c$, which implies dynamically unstable flow. Lapse rates within the smoke plumes were most often negative, or $\partial\theta/\partial z < 0$, and provide more evidence of plume instability. Additionally, on various profiles, winds shifted and or, increased within the smoke plumes, another indication of instability and turbulence.

The aerodynamic model created by Potter (2003) and altered by Clements et al. (2006) estimated water vapor released during the summer and winter burns quite well when compared to the radiosonde data. The model results are extremely sensitive to the value of H_M , as it alters the concentration by considering the volume of air affected by the smoke plume. Smoke plume moisture enhancement presented here is lower than that found by the tower based measurements. A balloon may not capture smoke plume structure as well as tower based measurements because towers are in direct passage of fire fronts, while the balloons ascend through more diluted smoke plumes. In any case, a composite plume profile has been produced (Fig. 48) to generalize all plume soundings. In general, a plume-induced moisture increase is present within the lowest 100 m AGL.

d. RC Airplane

The RC airplane was deployed during a prescribed burn conducted by Cal Fire at GP on 7 October 2008. The burn unit at GP was in a valley alongside a road that allowed for a favorable site to fly the RC airplane (Fig. 3). Since winds were southerly in the morning (Fig. 21), the northern edge was lit first. Ignition on the southern edge would be dangerous because southerly winds would rapidly drive the fire through the valley and quickly strengthen the fire front, potentially causing Cal Fire to lose control of the fire. Southerly winds carried smoke up the valley of GP and once a substantial smoke plume developed, the RC airplane was launched. The plane was flown in and out of the plume from the surface to ~ 400 m AGL for 41 min before re-fueling. While maintenance procedures were performed on the plane, winds took a northwesterly shift due to complex valley terrain and sea breeze penetration. This forced Cal Fire to change orientation of

the backing fire and the ignition line to the southern edge of GP. After the wind shift, northerly winds carried smoke down the valley and after another substantial smoke plume developed, the RC airplane was launched for a second flight. The same radiosonde was used for flight two due to uninterrupted communication between satellites, radio signal, and the field laptop computer. The pilot had better visual contact with the aircraft during the second flight, so was able to direct the plane closer to the flames. By this time, the pilot was also more comfortable with the plane and the turbulent effects from the fire. Flight two lasted ~ 43 min, ending as ignition was completed.

Radiosonde data from the RC airplane was analyzed similarly to test flights described in the Methods section. Figure 49 shows a 3-dimensional plot of flight path. The plot accurately shows warmer temperatures near the surface and closer to the surface, with cooler temperatures aloft as ambient air was entrained into the smoke plume. Water vapor mixing ratio was calculated from the Clausius-Clapeyron equation (Eq. 4). It can be seen from these two plots as temperature decreases, water vapor mixing ratio also decreases, which implies there is more water vapor in the plume; however, ambient atmospheric conditions may be such that less moisture is present away from the surface. It would have been beneficial to launch another radiosonde upwind of the burn unit, in the same location that the 0813 PDT sounding was obtained (Fig. 20). Considering the 0813 PDT sounding ~ 3 h before ignition, water vapor mixing ratio was ~ 6.0 g kg⁻¹ at the surface and decreased to ~ 3.0 g kg⁻¹ at 400 m, then increased until it reached the top of the boundary layer near 1000 m AGL (Fig. 20). This results in a $\partial q / \partial z = -0.0075$ g kg⁻¹ m⁻¹ and implies the ambient water vapor mixing ratio decreased throughout the

layer captured by the RC airplane. Therefore, it is necessary to consider altitude when determining temperature and moisture fluctuations due to the smoke plume.

Timeseries of temperature, water vapor mixing ratio, and altitude show correlations between these two variables, as well as height of the flight path (Fig. 50). Highest levels away from the fire and smoke plume correspond to cool temperatures and less moisture, while lowest levels near the fire front correspond to higher temperatures and more moisture. As altitude increased, and the plane flew further above the surface, temperature decreased. Altitude had to be corrected for because negative height resulted from the height difference from the runway to the fire on the lower valley floor. The radiosonde was initialized on a runway alongside the burn unit, ~ 6.7 and 12.4 m higher than the two separate burns, respectively.

Smoke plume moisture ranged from 5.6 to 8.4 g kg^{-1} with corresponding temperatures of 23.4 to $29.6 \text{ }^{\circ}\text{C}$ during flight one. At highest altitudes, moisture varied around 6.5 g kg^{-1} , while near the surface it remained near 7.5 g kg^{-1} . At 1205 PDT the RC airplane at ~ 350 m AGL and captured an ambient temperature of $23.5 \text{ }^{\circ}\text{C}$ and 6.8 g kg^{-1} , as the plane flew toward the surface, moisture and temperature increased to $28.0 \text{ }^{\circ}\text{C}$ and 7.5 g kg^{-1} at the surface near the fire front. This results in $\partial q / \partial z = -0.002 \text{ g kg}^{-1} \text{ m}^{-1}$. Since this rate is greater than that at the same level during the ambient morning sounding, moisture enhancement near the surface is due to the smoke plume and is on the order of 0.5 to 1 g kg^{-1} .

a)

b)

Fig. 49. Flight Path One in 3D: Flight path with temperature (a) and calculated water vapor mixing ratio (b) obtained from GP on 7 October 2008.

The northerly wind shift prior to flight two brought a moister air mass to GP and signifies the presence of the marine layer. Ambient moisture is, therefore, slightly greater during the second flight (Fig. 51). Ambient moisture between 0 to 100 m varied between 6.5 and 7.0 g kg⁻¹ and 9.0 to 10.0 g kg⁻¹ for flights one and two, respectively. The new air mass is not obvious when comparing the temperatures from flight one and two.

Fig. 50. Flight One: Timeseries of (a) temperature, (b) water vapor mixing ratio, and (c) altitude for flight one at GP on 7 October 2008.

Figure 51 shows smoke plume moisture ranged from 7.1 to 12.4 g kg⁻¹ with corresponding temperature increases from 23.0 to 31.5 °C. At highest altitudes and away from the fire, water vapor mixing ratio dropped to 7.0 to 8.0 g kg⁻¹, while ranged between

10.0 to 11.0 g kg⁻¹ near the surface. At 1317 PDT, the plane at the surface captures the highest temperatures and greatest moisture at 31.2 °C and 12.5 g kg⁻¹, respectively. Just prior to this at 1316 EST, the airplane still near the surface, but captured 27.1 °C and 9.5 g kg⁻¹. This implies a smoke plume moisture enhancement, at the same altitude, on the order of 2.2 g kg⁻¹.

Fig. 51. Flight Two: Timeseries of (a) temperature, (b) water vapor mixing ratio, and (c) altitude from flight two at GP on 7 October 2008.

Each flight was broken into multiple legs for a detailed analysis of height, temperature, and water vapor mixing ratio. An example is leg three from flight two and was plotted similarly to the full flights (Fig. 52).

When the plane was near the flames at the surface, temperature reached 31.5 °C and water vapor mixing ratio reached 12.5 g kg⁻¹ (Fig. 52). As the plane climbed to 300 m AGL, temperature and water vapor mixing ratio decreased to 23.8 °C and 8.5 g kg⁻¹, respectively. Flight two leg three shows temperature increase of 7.7 °C and a moisture increase of 4.0 g kg⁻¹ in an altitude change of 300 m. This results in $\partial q/\partial z = -0.01$ g kg⁻¹ m⁻¹, which is again greater than that obtained from the ambient morning sounding (Fig. 20). Moisture enhancement near the surface is, thus, due to the smoke plume and is on the order of 2.0 to 3.5 g kg⁻¹.

Fig. 52. Flight Two, Leg Three Timeseries: Timeseries of (a) temperature, (b) water vapor mixing ratio, and (c) altitude for flight two, leg three at GP on 7 October 2008.

The pilot was asked to fly the plane vertically away from the fire in clear air for as long and as high as possible to obtain a vertical profile of the ambient atmospheric environment and then to fly down directly into the smoke plume. This was done to create a virtual profile of ambient and plume conditions for further comparison. Vertical profiles of potential temperature, water vapor mixing ratio, and flight path from start to finish are shown in Fig. 53 for flight 2 leg one. Figure 53 shows moisture decreased from $\sim 9.0 \text{ g kg}^{-1}$ at the surface to $\sim 7.0 \text{ g kg}^{-1}$ at $\sim 400 \text{ m AGL}$, when the plane ascended in clear air. The potential temperature plot associates this layer with neutral stability or constant potential temperature. Then the plane descended into the smoke plume and moisture increased to $\sim 10.0 \text{ g kg}^{-1}$, and potential temperature implies an unstable layer until it reached the warmest temperatures of the fire near 200 m AGL . Cooler and drier air was then captured as the plane continued descending out of the smoke plume. This implies a smoke plume moisture enhancement on the order of 1.0 g kg^{-1} .

In summary, a RC airplane equipped with a small radiosonde has proved to be a cost effective and efficient way to measure *in situ* temperature and relative humidity in smoke plumes. Smoke plume moisture increased on the order of 0.5 to 1.5 g kg^{-1} for flight one and 2.0 to 3.5 g kg^{-1} for flight two. The radiosonde installed on the wing of the RC airplane is capable of producing many resources to analyze smoke plume structure. Analyses performed here have attempted to account for background atmospheric conditions and vertical structure of temperature and relative humidity. To accurately compare to ambient conditions and determine smoke plume moisture enhancement, a radiosonde launched upwind of the burn unit at time of ignition would be beneficial. A

camera attached to the RC airplane, and synched with the timestamp of the radiosonde on the wing, would help determine the location of the plane to the fire front and smoke plume.

Fig. 53. Flight Two, Leg Three Atmospheric Profile: Vertical profiles of (a) temperature, (b) calculated water vapor mixing ratio, and (c) start (green) and end (red) of flight path for flight two, leg one at GP on 7 October, 2008.

4. Conclusions

Unpredictable and unmanageable wildland fire spread causes near \$1B of property damage and destroys millions of acres of land annually in the US. Recent GCM forecasts an increase in fire frequency by 11 to 55% by 2099, thus, the need for understanding, predicting, and managing natural and prescribed fires will amplify. Three measurement platforms were utilized to measure temperature and moisture in smoke plumes. *In situ* measurements were obtained during various prescribed fires via stationary towers equipped with temperature and relative humidity probes, radiosondes, and a RC airplane with a radiosonde installed in the wing. The goal of these measurements is to better understand fire-atmosphere interaction at the fire front and within the smoke plume. Moisture released during combustion can enhance buoyancy from the resultant latent heat release (Potter 2002). Warm and moist surface conditions aid in vertical mixing and can create a dynamic fire front and smoke plume, which can lead to dangerous winds that drive the fire. Previous studies have shown a wide range of water vapor concentrations in smoke plumes (Potter 2005; Achtemeier 2006), but much uncertainty still exists in the quantitative values of moisture released during combustion. Quantitative values of smoke plume moisture enhancement were found by instruments on stationary and non-stationary platforms near the fire front and aloft.

Stationary towers were placed within burn units during R_xFEmEx Summer and Winter, GP, and FF, which allowed for temporal evolution of temperature and water vapor mixing ratio of a passing fire front to be determined. Seasonal comparisons were made due to identical fuels burned on six different occasions: three under moist summer

conditions and three under dry winter conditions. Major differences were identified between summer and winter prescribed burns and it became apparent that prescribed burns have seasonal characteristics. Ambient surface temperatures were $\sim 10\text{ }^{\circ}\text{C}$ warmer with surface humidity $\sim 10\text{ g kg}^{-1}$ greater in summer. This is a result of usual summertime warm and humid conditions present in the Southeastern US. Upon fire front passage, plume moisture increase was on the order of 3.8 to 10.4 g kg^{-1} during summer burns and 3.3 to 4.8 g kg^{-1} during winter burns. After applying the correction following Achtemeier (2006), these values increased to 5.7 to 29.9 g kg^{-1} and 5.7 to 8.3 g kg^{-1} , respectively. On average, corrected temperature increased moisture enhancement from observed by 1.5 to 2 times in magnitude.

Smoke plume temperature and water vapor mixing ratio were difficult to discern at GP due to the advection of a moist airmass into the valley from the north; however, temperature and water vapor mixing ratio captured at the tower increased by $7.5\text{ }^{\circ}\text{C}$ and 2.4 g kg^{-1} upon fire front passage, respectively. The correction following Achtemeier (2006) increased these values to $10.0\text{ }^{\circ}\text{C}$ and 3.7 g kg^{-1} , respectively.

A range of smoke plume temperature and moisture was observed during FF and is most likely due to multiple instruments used. The correction following Achtemeier (2006) could not be applied to the datasets because different relative humidity sensors were used with different response times. At the fire front, temperature and water vapor mixing ratio increased in ranges between 13.8 to $19.1\text{ }^{\circ}\text{C}$ and 1.0 to 3.1 g kg^{-1} , respectively, on the various instruments.

Multiple radiosondes were launched during Summer and Winter RxFEmEx to obtain *in situ* smoke plume profiles. This allowed for stability analyses and to determine Ri for various layers under, within, and above smoke plumes. For most profiles, $Ri < Ri_c$, which implies dynamically unstable flow. Only for two plume soundings was $Ri > Ri_c$, or stable flow within the plume layer. This occurred as a result of cooler air below the plume getting trapped or capped by warm plume air. Stronger winds and wind shifts were often observed near the plume as another indication of instability and turbulence.

Vertical profiles of potential temperature show lapse rates within the smoke plumes were most often negative and with strong potential temperature gradient. Additionally, on various plume profiles, winds shifted and/or increased from the pre-fire conditions, another indication of fire-induced modification of the atmospheric environment. Balloon measurements of water vapor mixing ratio in smoke plumes show increases from 0.7 to 2.5 g kg⁻¹ and 0.3 to 0.8 g kg⁻¹ during summer and winter, respectively.

Plume profiles were chosen for each burn and allowed for a detailed analysis of enhanced plume moisture as compared to ambient conditions. Summer plume water vapor mixing ratio profiles increased on the order of 1.2 to 2.2 g kg⁻¹, while winter plume profiles of water vapor mixing ratio increased by 0.4 to 0.8 g kg⁻¹. These values are much lower than observed by tower data, approximately a magnitude of 3.5 times lower.

A RC airplane equipped with a small radiosonde has proved to be a cost effective and an efficient way to measure *in situ* temperature and relative humidity within smoke plumes. Smoke plume moisture increased on the order of 0.5 to 1.5 g kg⁻¹ (2.0 to 3.5

g kg^{-1}) for flight one (two). These values agree with measurements made on the interior tower at GP.

Smoke plume moisture enhancement captured by the radiosondes aloft is less than that captured by the towers at the fire front during RxFEmEx. This is a result of ambient air entraining into the smoke plume at higher levels. More moisture released in the Summer RxFEmEx burns is a result of more available ambient moisture in the atmosphere leading to increased fuel moisture content.

Significant findings from this study include:

- Greater moisture enhancement near the surface at the fire front captured by the towers than aloft captured by the radiosonde. This may be due to entrainment of drier ambient air into the smoke plumes.
- Seasonal variations show more moisture enhancement observed on the towers and radiosondes for the summer (wet season) than the winter (dry season).
- A standard correction may overestimate smoke plume moisture enhancement as it is sensitive to its lag index and amplitude factor parameters.
- Smoke plume moisture enhancement estimated by a bulk aerodynamic model is underestimated when compared to surface observations, but is closer in magnitude to that obtained aloft by the radiosondes.
- The RC airplane is a useful measurement platform for smoke plume studies.

An evaluation of the strengths and weaknesses of the measurement platforms and instruments used in this study is necessary for future observations of smoke plume moisture enhancement. Measurements obtained on the towers by the HMP45C paired with the thermocouple may be skewed. These fire environments greatly exceed the temperature thresholds intended from the instruments. Also, the two sensors on the HMP45C have different response times, with the temperature sensor responding every 15 min and the relative humidity sensor sampling every 5 s. Due to these different response times, corrections had to be applied to the datasets to adjust the temperature lag. This allows for further error, as the lag and amplitude parameters in the correction are highly sensitive. A fast response water vapor mixing ratio sensor that can withstand extreme temperatures is ideal for observing smoke plume moisture enhancement. This would also alleviate any room for errors in the calculation from temperature and relative humidity to water vapor mixing ratio.

Observations obtained by the radiosondes were difficult to determine smoke plume moisture enhancement due to lack of knowledge of ambient atmospheric conditions. With additional radiosondes and data acquisition equipment, soundings could be made simultaneously upwind of the burn unit. This would allow for a more precise value of moisture enhancement due to the smoke plume.

In regards to the RC airplane, future data acquisition should include a sounding obtained upwind of the burn unit while the RC airplane captures the smoke plume, to obtain an ambient vertical profile for direct comparison. A camera mounted on the RC airplane or a video of the entire flight path from the ground is needed to validate the

plane in ambient air or inside the smoke plume. Two cameras mounted at right angles would be ideal to obtain the best possible perception.

Limitations as well as strengths and weaknesses of the various sensors and measurement platforms have been identified. Future work should consider these issues to better capture smoke plume moisture enhancement.

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APPENDIX: Radiosonde Response Time

Fig. A.1. Temperature Response Time: Time constant for thermistor on radiosonde.

Fig. A.2. Relative Humidity Response Time: Time constant for relative humidity capacitor on radiosonde.