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Application of a Mini Unmanned Aircraft System for In Situ Monitoring of Fire Plume Thermodynamic Properties

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ABSTRACT

Direct measurements of wildland fire plume properties are rare because of difficult access to regions near the fire front and plume. Moisture released from combustion, in addition to added heat, can enhance buoyancy and convection, influencing fire behavior. In this study, a mini unmanned aircraft system (miniUAS) was used to obtain in situ measurements of temperature and relative humidity during a prescribed fire. The miniUAS was successfully maneuvered through the plume and its associated turbulence and provided observations of temperature and humidity profiles from near the centerline of the plume. Within the plume, the water vapor mixing ratio increased by 0.5–3.5 g kg^{-1} above ambient and was caused by the combustion of fuels. Potential temperature perturbations were on the order of 2–5 K. These results indicate that significant moisture and temperature enhancement can occur and may potentially modify convection dynamics of fire plumes.

1. Introduction

Wildland fires present a difficult environment for making atmospheric observations because of the extreme heat generated by the fire front and the resulting turbulence within the smoke plume. Direct measurements of the atmospheric environment near fires are rare. While recent efforts have been made to measure fire–atmospheric interactions and turbulence during experimental fires, measurements are typically limited to tower-based platforms placed strategically to avoid extreme heat flux (Clements et al. 2007; Clements 2010).

It has been suggested that combustion of wildland fuels increases the fire plume water vapor content (Potter 2005) resulting in increased buoyancy and altering the dynamics of the fire plume. Potter (2005) investigated the role of water vapor on fire–atmosphere interactions by revisiting early studies of large-scale forest fires that resulted in pyrocumulus cloud formation above smoke plumes. He found the lifted condensation level (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 to the plume. Other cases revealed a plume height up to 13 km where the ambient equilibrium level (EL) only reached 9.9 km, requiring an additional 3 g kg^{-1} and 3°C of moisture and temperature increase, respectively. The lower LCL and higher EL imply increased moisture in smoke plumes, which strengthen convective columns above fires. A study by Jenkins (2004) found that vertical smoke column development was most significant when the boundary layer lapse rate was adiabatic and when low-level humidity was relatively high, corroborating Potter's hypothesis.

The importance of moisture released from fires in determining plume buoyancy and convection has been questioned. Simulations by Luderer et al. (2009) showed 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

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6 times greater, ranging from 6.6 to 35 g kg^{-1}. The authors claimed this water vapor enhancement is unrealistically high, but these results are within range of that measured by Clements et al. (2006) and Achtemeier (2006) during smoldering combustion.

Luderer et al. (2006) suggest water emissions from fires can be neglected upon investigation of pyro-convection after they found it has roughly a 5%–10% effect on pyro-cumulus formation. Parmar et al. (2008), on the other hand, found ratios between 1.2 and 3.7 for water formation per carbon emitted during combustion chamber experiments and that the water comes from within the inside cells of the vacuoles. They suggested that fuel moisture can make a significant contribution to the water vapor content of fire plumes and that the low water vapor contribution proposed by Luderer et al. (2006) may be an underestimate as a result of their assumed low fuel moisture content. Parmar et al. indicate that accurate measurements of water vapor release from biomass burning under field conditions are needed to constrain future modeling efforts.

In comparison to the number of theoretical or laboratory studies relating to moisture in fire plumes, few field observational studies have measured the temperature and moisture characteristics of fire plumes (Clements 2010). Therefore, the goal of this study is to directly measure fire plume temperature and humidity properties in order to quantify water vapor release in wildland fires. To accomplish this, an inexpensive unmanned aircraft system (UAS) was deployed and tested for monitoring the thermodynamic structure of wildland fire plumes in close proximity to the actively burning fire fronts.

2. Methods: Platform description and experimental design

The difficult nature of obtaining meteorological data in and around wildland fires requires a platform that can access the fire plume without endangering personnel and damaging equipment. Access to the plume is difficult since the plume is usually advecting downwind, so the platform must be mobile to follow the plume. Additionally, since the fire environment can potentially damage the platform and cause complete loss of the instrumentation, the platform has to be inexpensive and disposable. To achieve these goals, a remote controlled (RC) hobby airplane was chosen and instrumented with a commercially available radiosonde (Graw, Inc., DFM-06). Additionally, an RC airplane can be manually controlled to fly in and out of the plume at multiple levels up to ~400 m AGL.

Previous studies using a UAS have shown the platform's utility in the atmospheric sciences (e.g., Mach et al. 2005; Ramanathan et al. 2007; Houston et al. 2012). Additionally, high-altitude wildfire research and monitoring have been significantly improved using UASs (Ambrosia et al. 2004). Even as early as the late 1960s the U.S. Forest Service (USFS) deployed RC aircraft to remotely sense wildfires (F. Fujioka 2011, personal communication). A comprehensive review of UAS use in atmospheric research has been conducted by Houston et al. (2012).

The mini unmanned aircraft system (miniUAS) was deployed during a prescribed grass fire on 7 October 2008 (Fig. 1a) that was conducted east of San Jose, California, by the California Department of Fire and Forestry. A detailed description of the burn conditions and site is given by Seto and Clements (2011). To minimize instrument cost, the system did not include any flight automation and was operated manually by a volunteer RC pilot/operator. The miniUAS was successfully maneuvered through the plume and its associated turbulence and provided observations of in situ plume temperature and humidity profiles from the centerline of the plume. Potential temperature was calculated from these variables to more directly compare temperatures at altitude thus minimizing temperature differences due to the ambient environmental lapse rate.

a. MiniUAS platform

The miniUAS was developed using a small RC model airplane (Hobbico Avistar 40 II MonoKote ARF airframe) chosen for stability and performance during flight. The completed UAS measures 1.5 m in wingspan and 1.2 m from propeller to rudder (Fig. 1a). The radiosonde was mounted on the underside of the left wing and enclosed in polystyrene thermal insulation for protection (Fig. 1b). The DFM-06 radiosonde from Graw, Inc., is the lightest commercially available at less than 90 g. The data output from the sonde is 1 Hz; however, independent tests of the response time of the radiosonde's thermistor and capacitive hygrometer were conducted using hot and cold water baths. Results from these tests indicated that there was some hysteresis between the ambient air to hot bath and the hot bath to ambient air and that the actual response times of the thermistor and hygrometer were 2.1 and 1.7 s, respectively. The response time of the sensors was adequate given the speed of the UAS (~4 m s^{-1}) and the precision of the radiosonde's GPS.

b. Experimental design

The experimental flights were made during a prescribed fire that was conducted in a 100-acre plot consisting of fully cured, tall-grass fuels (Seto and Clements 2011). Two flights were made during the burn with flight 1 lasting 41 min in length and reaching altitudes of ~400 m AGL, while flight 2 lasted ~43 min, ending as

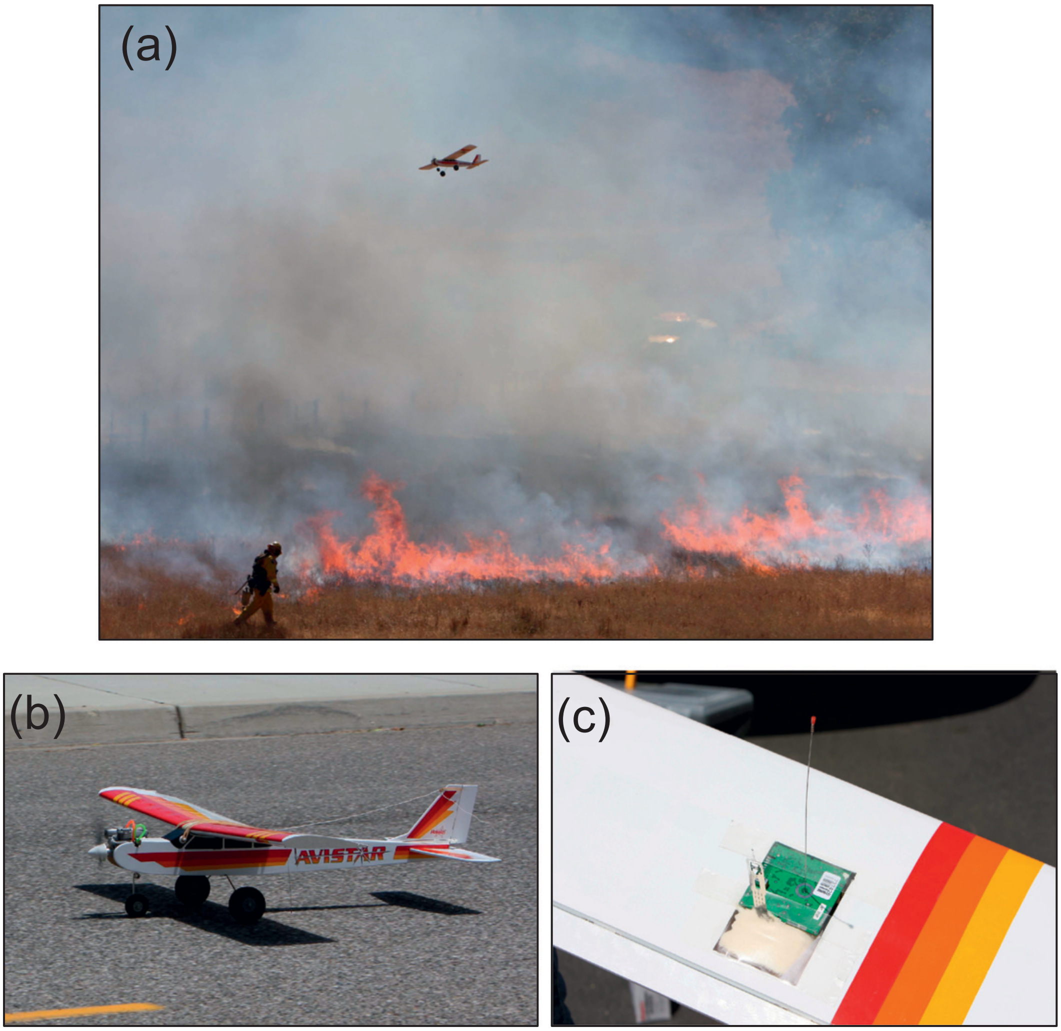

FIG. 1. (a) The miniUAS during the research flight on 7 Oct 2008, (b) completed miniUAS system during the test flight, and (c) Graw, Inc., DFM-06 radiosonde installed in the left wing of the Hobbico Avistar 40. The sensor probe extends below the wing by 10 cm allowing for good exposure to airflow.

burning operations were completed. Figure 2 shows the experimental layout and design of the flights. The burn operations were conducted under backing fire conditions (fire front burning into the wind). A micrometeorological tower was placed in the middle of the burn unit and a portable weather station was placed downwind (Fig. 2). The flight plan was designed to sample smoke from the fire using flight paths aligned across the burn plot and vertical profiles centered within the plume, ideally at the plume centerline. Because of the requirement for continuous visual contact between the pilot in command (PIC) and the UAS, the actual flight paths were determined based on plume and fire line conditions. The low intensity of the burn created less dense smoke even in the main convection core allowing the UAS to sample most of the smoke columns observed.

In wildfire science, research operations are under the direction of the Incident Commander (IC) and must follow the protocol of the National Incident Command System (ICS) as the safety of all personnel is a priority. Our proposed flight plan and operations were under the Cal Fire Incident Command, which was operating a UH-1H Super Huey helicopter at the incident for training purposes. The IC was managing the airspace for the burn operations. This included communications between the RC pilot/spotter, the helicopter pilot and crew, and Air Traffic Control (ATC). The RC pilot and spotter were in radio contact with the IC at all times. This was to ensure that our flights were only conducted when the UH-1H was grounded and not in the air. The helicopter pilot was briefed with the IC and RC pilot during the incident briefing at 0700 PDT (Pacific

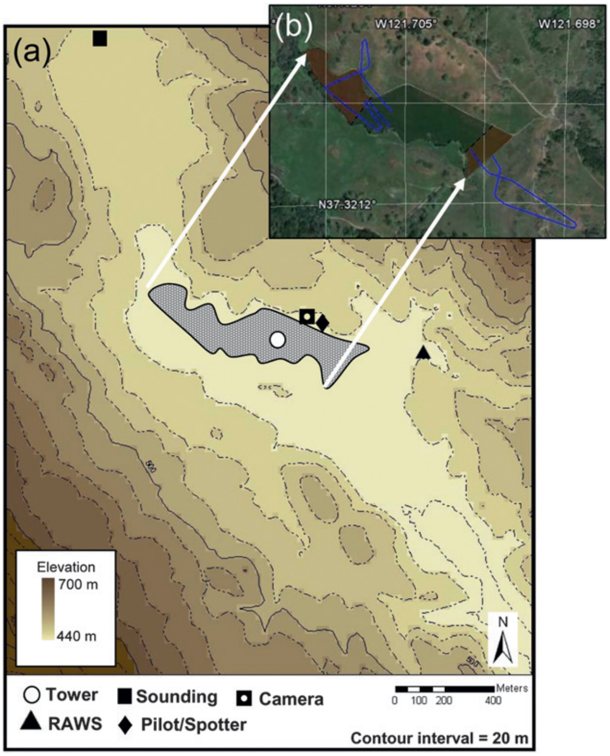

FIG. 2. (a) Topographic map indicating the burn unit (shaded area) and instrument locations. (b) Inset map shows the general location of the two flight paths (blue line).

daylight time) before firing operations began. Operation of UAS requires Federal Aviation Administration (FAA) authorization (Houston et al. 2012). Our project was tied to the IC and its temporary flight restrictions for the area of the incident operations and thus was exempt from specific authorization. A thorough discussion of FAA UAS flight requirements and protocol are summarized in the study by Houston et al. (2012).

3. Results and discussion

Data from the flights were analyzed to determine the thermodynamic structure of the plume and near-surface environment close to the fire front, and whether or not this small and lightweight platform could be used in such an application. A 0813 PDT radiosonde sounding (not shown) was released ~1 km northwest of the burn perimeter (Fig. 2) ~3 h before ignition. The water vapor mixing ratio was ~6.0 g kg^{-1} at the surface and decreased to ~3.0 g kg^{-1} at 400 m AGL, then increased until it reached the top of the boundary layer near 1000 m AGL, which implies the ambient water vapor mixing ratio decreased throughout the layer captured by the miniUAS. The decrease in mixing ratio at 400 m AGL was associated with a shallow and elevated layer of drier air that was advected by drainage winds that entered into the narrow valley from the northeast.

Time series of potential temperature, water vapor mixing ratio, and altitude are analyzed to show the impact of the fire plume on potential temperature, water vapor mixing ratio, as well as height of the flight path (Figs. 3–5). Highest levels away from the fire and smoke plume correspond to cool temperatures and less moisture, while lower levels near the fire front correspond to higher temperatures and more moisture. Smoke plume moisture ranged from 5.6 to 8.4 g kg^{-1} with corresponding potential temperatures of 300–305 K during flight 1 (Fig. 3). At the 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 miniUAS was at an altitude of ~350 m AGL and measured an ambient potential temperature of 303 K and mixing ratio of 6.8 g kg^{-1}. As the UAS flew toward the surface, moisture and potential temperature increased to 7.5 g kg^{-1} and 304.5 K, respectively, near the fire front. This results in $\delta q/\delta z = -0.002$ g kg^{-1} m^{-1}. Because this rate is greater than that at the same level during the ambient morning sounding, moisture enhancement near the surface is likely due to the smoke plume and is on the order of 0.5–1 g kg^{-1}.

An afternoon sea-breeze surge occurred just before flight 2 and brought an air mass with increased moisture to the valley atmosphere indicating the presence of the marine layer (Seto and Clements 2011). Ambient moisture was, therefore, slightly greater during the second flight (Fig. 4). Ambient moisture between 0 and 100 m AGL varied between 6.5–7.0 and 9.0–10.0 g kg^{-1} for flights 1 and 2, respectively. Additionally, the turbulence kinetic energy was ~5 m^2 s^{-2} measured at the base of the plume (Seto and Clements 2011) indicating that the miniUAS was effective at handling the moderate turbulent conditions within the plume.

Figure 4 shows increases in the smoke plume mixing ratio from 7.1 to 12.4 g kg^{-1} with corresponding potential temperature increases from 301 to 307.5 K during flight 2. At the highest altitudes and away from the surface and fire front, the water vapor mixing ratio dropped to 7.0–8.0 g kg^{-1}, while it ranged between 10.0 and 11.0 g kg^{-1} near the surface. At 1317 PDT, the UAS captured the highest temperatures and greatest moisture at 307.5 K and 12.5 g kg^{-1}, respectively. Just prior to this at 1316 PDT, the UAS was still near the surface, but measured a potential temperature of 302.5 K and a water vapor mixing ratio of 9.5 g kg^{-1}. While it might be expected to have much greater potential temperature near the fire front, Clements (2010) showed that there exists strong entrainment of ambient air into the fire plume even in the lowest 10–20 m above the fire front. The position of the UAS at that time was also documented

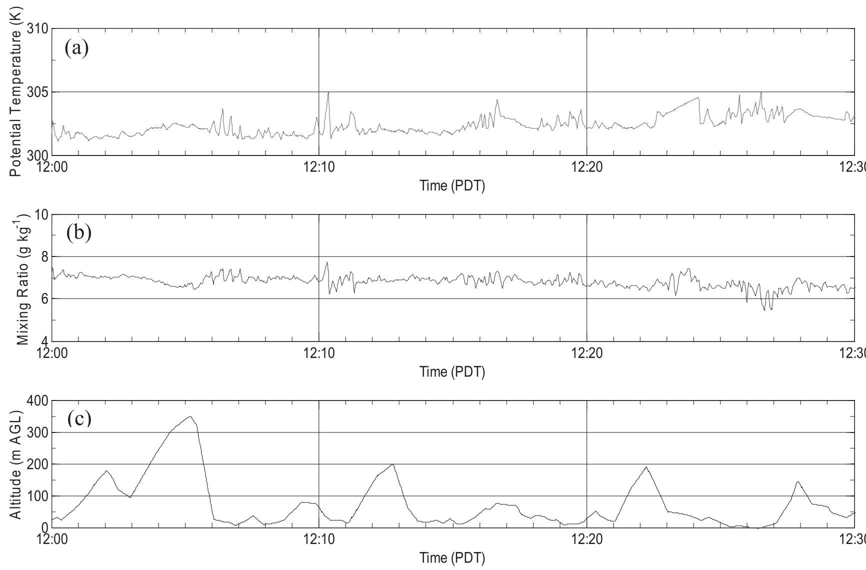

FIG. 3. Time series of the (a) potential temperature, (b) water vapor mixing ratio, and (c) altitude for the entire duration of flight 1 during the prescribed fire deployment on 7 Oct 2008.

in time-lapse photos (not shown). These results indicate that a smoke plume moisture enhancement of approximately 2.2 g kg^{-1} was observed.

To diagnose the plume penetration further, each flight was broken into multiple legs for a detailed analysis of height, potential temperature, and water vapor mixing ratio. An example is leg 3 from flight 2 (Fig. 5). When the UAS was near the fire front at the surface, the plume potential temperature of 307.5 K and water vapor mixing ratio of 12.5 g kg^{-1} was measured (Fig. 5). As the UAS climbed to 300 m AGL, the potential temperature and water vapor mixing ratio decreased to 302 K and 8.5 g kg^{-1}, respectively. More striking is the fact that from 1316 to 1317 PDT, the UAS remained near the ground and as it moved away from the fire front, the potential temperature dropped 5 K and the water vapor dropped by approximately 2 g kg^{-1}. Flight 2, leg 3 shows a potential temperature increase of 5 K and a moisture increase of 4.0 g kg^{-1} in an altitude change of 300 m. This results in $\delta q/\delta z = -0.01$ g kg^{-1} m^{-1}, which

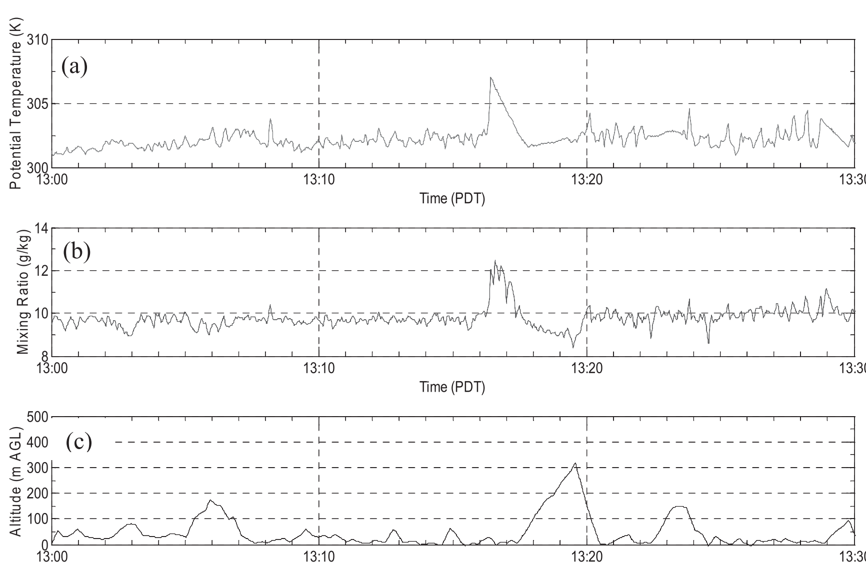

FIG. 4. Time series of the (a) potential temperature, (b) water vapor mixing ratio, and (c) altitude from flight 2 during the prescribed fire deployment on 7 Oct 2008.

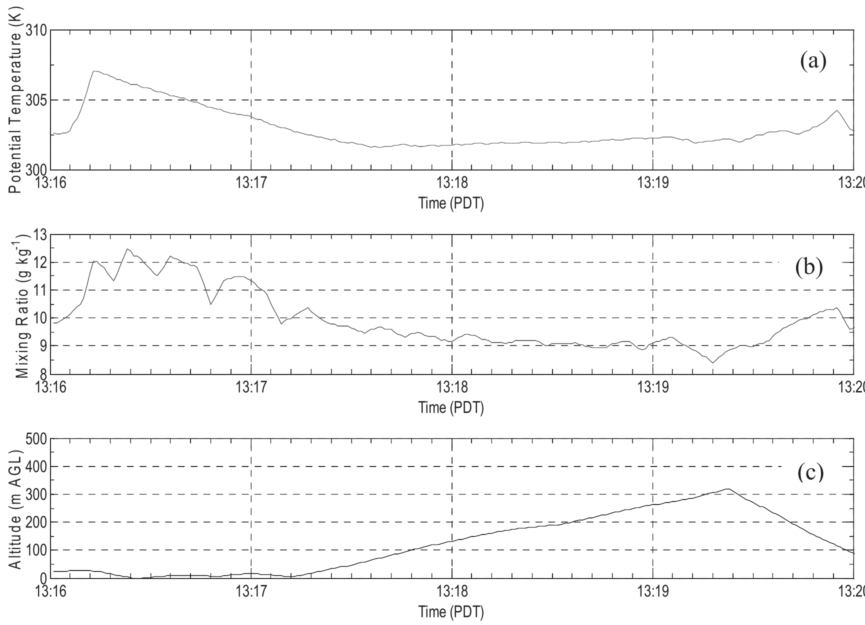

FIG. 5. Time series of the (a) potential temperature, (b) water vapor mixing ratio, and (c) altitude for leg 3 of flight 2, during the prescribed fire deployment on 7 Oct 2008.

is again greater than that obtained from the ambient morning sounding. Moisture enhancement near the surface is thus due to the smoke plume and is on the order of 2.0–3.5 g kg^{-1}.

One exciting application of a UAS is the potential to conduct soundings in order to obtain vertical profiles of temperature and humidity within the plume. To accomplish this, 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 was then instructed to fly downward directly into the smoke plume. This was done to create profiles of both ambient and plume conditions for comparison. Vertical profiles of the potential temperature and water vapor mixing ratio are shown in Fig. 6 for flight 2, leg 3. Moisture decreased

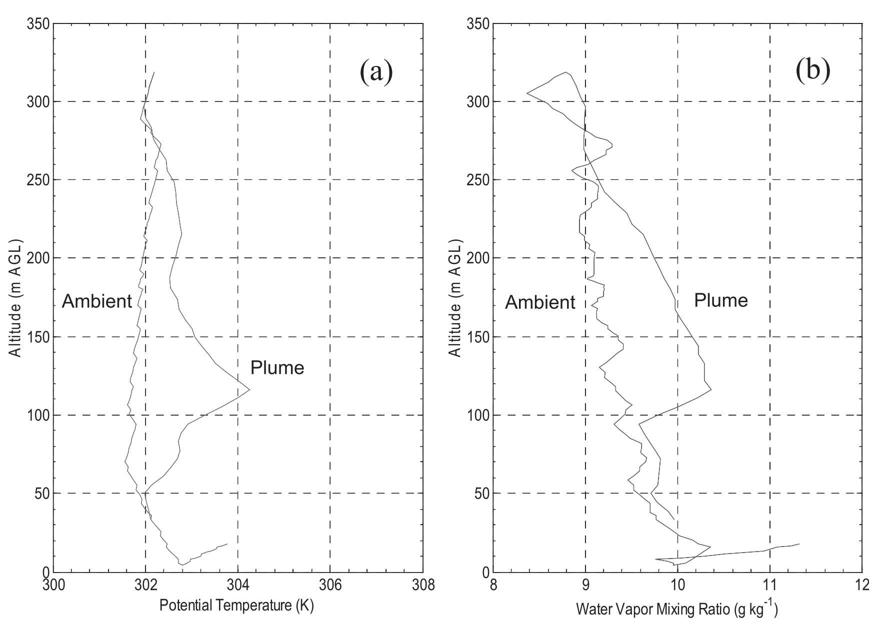

FIG. 6. Vertical profiles of the (a) temperature and (b) calculated water vapor mixing ratio of flight path for flight 2, leg 2 during the prescribed fire deployment on 7 Oct 2008.

from ~10.0 g kg^{-1} at the surface to ~8.5 g kg^{-1} at ~315 m AGL, when the plane ascended outside and upwind of the plume. The potential temperature profile indicates that the stability of this layer was neutral to weakly stable as shown with the nearly constant potential temperature with height. The slight increase in stability can be attributed to an increase in higher potential temperature air associated with the plume. The UAS then descended into the smoke plume and as it did, the water vapor mixing ratio increased to ~10.2 g kg^{-1} at an elevation of 125 m AGL. The plume air was approximately 2.5 K warmer than ambient at this layer. Cooler and drier air was then measured as the UAS continued its descent out of the smoke plume. Observed water vapor mixing ratio enhancement in the smoke plume was ~1.0 g kg^{-1}.

4. Summary and conclusions

An RC airplane equipped with a small radiosonde has proved to be a cost-effective and efficient way to measure in situ temperature and humidity in wildland fire smoke plumes. The smoke plume water vapor mixing ratio increased on the order of 0.5–1.5 g kg^{-1} for flight 1 and 2.0–3.5 g kg^{-1} for flight 2. The radiosonde installed on the wing of the RC airplane was capable of providing high temporal and spatial data for analyzing the smoke plume thermodynamic structure and was a cheaper and more efficient platform than the use of weather balloons. Additionally, the miniUAS allowed for thermodynamic mapping at predetermined locations within the plume.

The miniUAS was used effectively to obtain vertical atmospheric profiles in the smoke plume. The virtual sounding of the ambient atmosphere upwind of the plume indicated nearly neutral stability while the plume was unstable. The maximum potential temperature within the plume was ~2.5 K higher than the surrounding ambient air at an altitude of 125 m AGL. Below this level, air was slightly cooler and drier due to the UAS flying out and away from the plume.

Analyses performed here have attempted to account for the vertical structure of the potential temperature and water vapor mixing of a wildland fire plume. These results show that the moisture produced by the combustion of grass fuels can increase the plume moisture content by 0.5–3.5 g kg^{-1} above the ambient moisture content, potentially modifying the convection dynamics of fire plumes.

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