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# *In situ* measurements of water vapor, heat, and $CO_2$ fluxes within a prescribed grass fire

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*Abstract.* Fluxes of water vapor, heat, and carbon dioxide associated with a prescribed grass fire were documented quantitatively using a 43-m instrumented flux tower within the burn perimeter and a tethered balloon sounding system immediately downwind of the fire. The measurements revealed significant increases of temperature (up to 20°C), heat flux (greater than 1000 W m$^{-2}$), and $CO_2$ (larger than 2000 parts per million by volume) within the smoke plumes, as well as an intensification of turbulent mixing. Furthermore, the observations revealed an increase in water vapor mixing ratio of more than 2 g kg$^{-1}$, or nearly 30% over the ambient air, which is in good agreement with theoretical estimates of the amount of water vapor release expected as a combustion by-product from a grass fire. These observations provide direct evidence that natural fuel-load grass-fire plumes may modify the dynamic environment of the lower atmosphere through not only heat release and intense mixing, but also large addition of water vapor.

## Introduction

Wildland and prescribed fires are known to change atmospheric environments by producing heat and chemical species such as carbon dioxide. Less recognized in the meteorology literature is the fact that fires can also modify the dynamic conditions of the lower atmosphere by altering the moisture content of the air. Few studies have discussed the release of moisture by fires and these mostly with only indirect acknowledgement (Stocks and Flannigan 1987; Goens and Andrews 1998). In a recent paper, Potter (2005) presented theoretical arguments that combustion of plant fuels during forest and range fires may add as much as 5 g of water vapor to 1 kg of plume air and that this moisture can have a significant impact on the dynamics of the fire's convective plume.

Direct measurements of the amount of heat and water vapor released during an actual forest or range fire are very difficult to obtain, due largely to the dangers of the fire environment. In many cases, either the researcher or the equipment would be in danger of injury, damage, or destruction. In others, the duration and location of a fire may preclude instrument deployment. While aircraft may fly through fire plumes, their altitude and speed may dilute any moisture signal to such an extent that measurements are inconclusive.

Achtemeier (2003) measured temperature and relative humidity in the smoke rising from small smoldering patches. For these smoke plumes, comparable in size to the smoke from a campfire, observations showed dew-point temperatures roughly 10°C above ambient, with the largest measured dew-point temperature of 26°C above ambient. These results show direct evidence of moisture produced by small fire plumes.

From 1964 through 1967, the US Forest Service and the US Department of Defense cooperated in a study called Project Flambeau (Bush *et al*. 1969; Countryman 1969; Storey 1969). The goal of this study was to understand the possible consequences of widespread urban fires initiated by nuclear attack. These fires were simulated by simultaneously igniting piles of logging slash in arrangements comparable to the arrangement of houses in a city. Although this study focused on fires that were quite different from natural wildland fires, measurements of water vapor concentrations were made on two of the fires (460-7 and 760-1, as documented in Storey [1969] and Bush *et al*. [1969]). Fire 460-7 was 30 acres in size, involved 170 t per acre of Pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*), and produced water vapor mixing ratios over 30 g kg$^{-1}$ against a background of 3 g kg$^{-1}$. Fire 760-1 was 5 acres in size, used 33 t per acre of the same fuels and produced water vapor mixing ratios over 60 g kg$^{-1}$.

Achtemeier (2003) and the Project Flambeau fires represent two extremes of size and fuel load, leaving open the question of how much water a more typical landscape fire adds to air in its convective plume. Fire behavior, convection, and turbulent diffusion are independent, highly non-linear

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processes, and simply interpolating from the two extremes considered earlier to the fuel and spatial scales of a landscape fire is not physically sound.

In February 2005, a rare opportunity arose for measuring possible moisture fluxes from a prescribed prairie burn near the Texas Gulf Coast in the southern USA. Herein, we describe measurements taken using a flux tower and a tethered balloon sounding system during this burn. While the flux tower's purpose is much broader than just fire fluxes, its location within the burn perimeter and the opportunity to place a tethersonde downwind of the burn allowed measurements of water vapor as well as heat and $CO_2$ fluxes due to the burn. The measurements are used to evaluate estimates from bulk theoretical calculations of the amount of added water vapor to the atmosphere from a fire.

## Site, instrumentation, and synoptic conditions

The observations of the prescribed burn took place at the Houston Coastal Center (HCC) located in central Galveston County near La Marque, Texas ~45 km south-east of the Houston metropolitan area and 22 km from the western shores of Galveston Bay. HCC has a number of small-to-medium-sized prairies that are categorized as Texas Gulf Coast tall-grass prairies consisting of a mixture of native grasses including Big bluestem (*Andropogon gerardi*), Little bluestem (*Schizachyrium scoparium*) and Long-spike tridens (*Tridens strictus*). The prairie that was burned (Fig. 1) is 155 acres (0.63 $km^2$) in size and is considered one of the largest, undisturbed coastal prairies on the Gulf Coast of the USA. At the time of the prescribed fire, spring vegetation was just beginning to emerge and the cured, dead grasses from the previous year remained exposed and available for the fire to consume.

The synoptic conditions on the day of the prescribed burn (17 February 2005) were typical of a post-frontal environment with no precipitation. As shown in Fig. 2 by the 0600 central standard time (CST) rawinsonde sounding from Lake Charles, LA (the closest upper-air sounding site to Houston), a shallow layer of relatively colder and drier air moved through the region the previous night in the form of a shallow cold front. Winds near the surface were 5–7 m $s^{-1}$, from the north-north-east and prevailed throughout the period of the prescribed burn. Above this shallow layer (>500 m above ground level [AGL]) winds were westerly.

During the prescribed burn, measurements of turbulent heat, water vapor, and $CO_2$ fluxes were obtained by instruments mounted on a 43-m guyed tower located in the northern half of the prairie (Fig. 1). High-frequency momentum and temperature were measured using an 81000 3-D sonic anemometer (R. M. Young, Traverse City, MI, USA) at a height of 9.8 m AGL while a Li-Cor 7500 open-path infrared gas analyser (LI-COR Biosciences, Lincoln, NE, USA) collected high-frequency data of $CO_2$ and $H_2O$ concentrations. A CR-5000 data logger (Campbell Scientific, Logan, UT, USA) sampled both instruments at a frequency of 10 Hz, and turbulent fluxes were computed using eddy-covariance techniques. In addition to turbulent fluxes, 5-min mean meteorological variables were also measured at three levels (3, 22, and 32 m) using CS-500 temperature–humidity probes (Campbell Scientific) and propeller anemometers (5103; R. M. Young). The mean variables were recorded using a CR-23X data logger (Campbell Scientific) every 1 s and averaged for 5 min. The week leading to the day of the prescribed fire had sufficient rainfall so that the soil was nearly saturated. There was standing water at the base of the instrument tower, extending several meters outward and providing a small protective area for the tower where fire would not penetrate and risk damaging the instruments.


**Fig. 1.** Map of experiment site and instrument locations. Tower location is indicated by the large x and the location of the tethersonde system is indicated by the circle. The prairie perimeter is indicated by the solid box. The back burn along the south-west corner is indicated by the dashed line A, the ignition is indicated by lines B, C, and D. The solid arrows indicate direction of fire spread.

A tethered balloon sounding system (DigiCORA TT12; Vaisala, Boulder, CO, USA) was also placed downwind of the fire at the far south-west corner of the prairie (Fig. 1) to provide vertical profiles of temperature, relative humidity, wind speed, and wind direction at a frequency of 1 s. While the

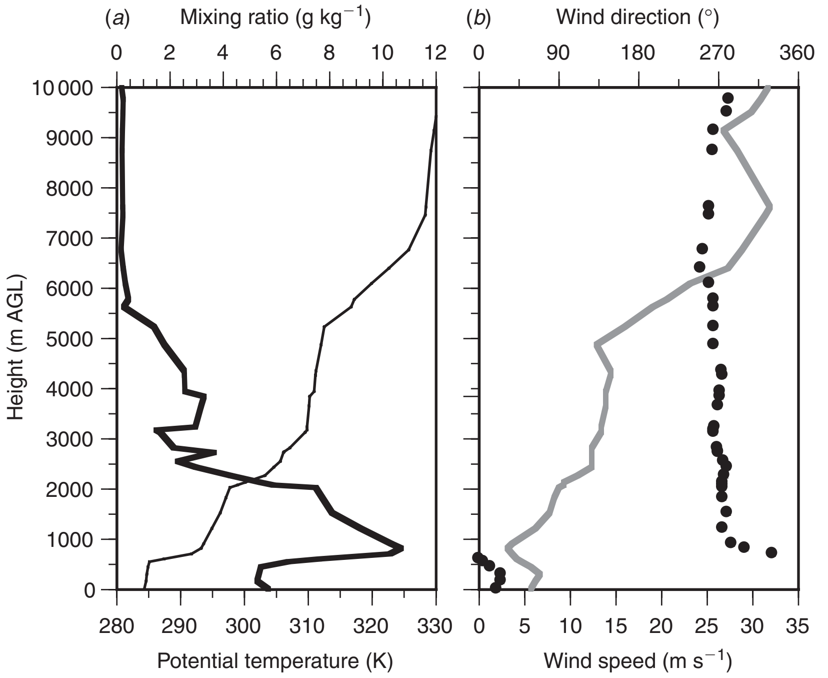


**Fig. 2.** Vertical profiles of (*a*) potential temperature (thin solid line) and mixing ratio (heavy solid line), and (*b*) wind speed (gray line) and wind-direction (black circles) at Lake Charles, LA, for the day of the burn, 17 February 2005, at 0600 central standard time.

original plan was to make continuous soundings throughout the entire burn period, strong winds with gusts of ~12 m $s^{-1}$ and heavy smoke from the fire forced the balloon operators to terminate the measurements after the first sounding taken around 0910 CST, right after the start of the back burn (a small control burn before the initial prairie is burned).

An initial back burn was started at 0900 CST in the south-west corner and continued for ~150 m (Fig. 1, line A). Fire-crew members with drip torches then (~0940 CST) lit additional back-fires to create protected perimeters around the radio shed just west of the instrument tower and around the guy-wires supporting the instrument tower. When these fires had progressed to the point where the fire-burn boss was assured the structures were safe, the crew resumed ignition along the southern edge of the field (Fig. 1, line B), proceeding counterclockwise until they reached the edge of the wooded area (Fig. 1, line C), approximately in the middle of the prairie's northern boundary. Ignition was continued on the western side of the wooded area (Fig. 1, line D). At this point, the fire ran with the wind until it reached the water-filled ditch on the west side of the field or the back-burn area on the southern edge. Active burning was complete by ~1045 CST, with smoldering continuing for several hours in parts of the field.

## Results and discussion

### *Tethersonde measurements*

The potential temperature and water vapor mixing ratio (g of water vapor per kg of dry air) profiles measured by the single tethersonde sounding during the preliminary back-burning of the southern perimeter of the prairie are shown in Fig. 3. The atmosphere in the boundary layer was near neutral, as revealed by the potential temperature profile that was nearly constant with height. The lower atmosphere was also quite dry for the coastal environment in Galveston, with a boundary layer water vapor mixing ratio around 6 g $kg^{-1}$, as compared to the more typical value of over 10 g $kg^{-1}$ for this time of the year.

Although the area of the back burn was only ~75 $m^2$, the plume generated by the fire was clearly visible in the tethersonde sounding profile obtained ~50 m downwind from the back burn. As indicated by a sudden increase in potential temperature and water vapor mixing ratio in the vertical profile, the fire plume had an approximate thickness of 10 m centered around 20 m AGL. The sharp decrease of both temperature and mixing ratio within the plume suggested that the plume was actually comprised of two layers each of ~5 m in thickness. Potential temperature increased from 285.8 K to 291.4 K in the lower layer and from 286.1 K to 288.8 K in the upper layer. While this plume did not represent the main plume from the full prairie burn, it did indicate a dramatic increase in not only the potential temperature, as would be expected, but also in water vapor. The mixing ratio of water vapor in Fig. 3 increased from 6.08 g $kg^{-1}$ to 8.01 g $kg^{-1}$ in the lower layer and from 5.67 g $kg^{-1}$ to 6.86 g $kg^{-1}$ in the upper layer (changes of 1.93 g $kg^{-1}$ and 1.19 g $kg^{-1}$, respectively). The net moisture increase of 1–2 g $kg^{-1}$ (20–30% of the background moisture) was notable, considering the small area of the back burn.

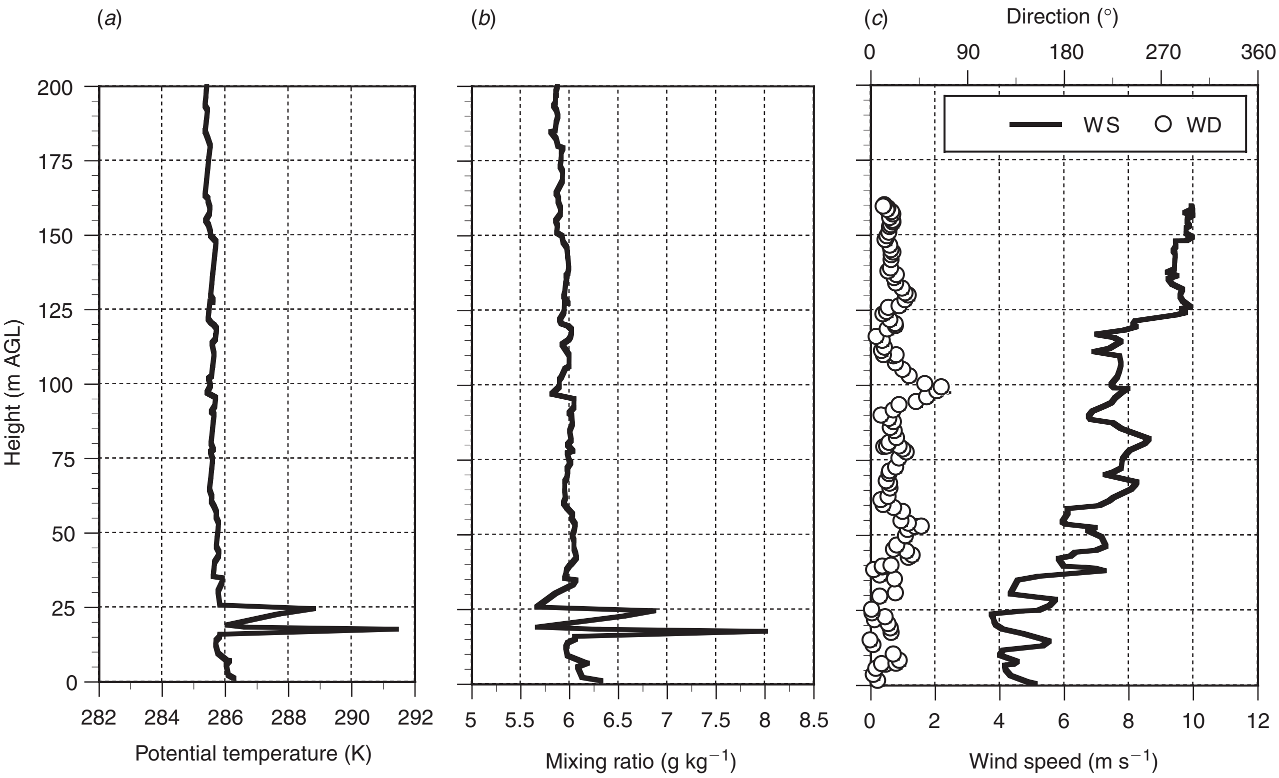


**Fig. 3.** Vertical profiles of (*a*) potential temperature, (*b*) mixing ratio, and (*c*) wind direction (WD) and speed (WS) from the tethersonde measurements taken during the preliminary back-burn at 0910 central standard time.

*Tower measurements*

While 5-min averaged quantities did not show the changing atmospheric conditions during the burn in great detail, there were some interesting features that warrant mention. The time series of the mean temperature, mixing ratio, and wind speed from the three levels on the tower are shown in Fig. 4. In the morning hours before the burn, the mean temperature decreased from the lower to higher levels at a rate close to the adiabatic lapse rate (~1°C per 100 m increase in height), indicating a neutral surface layer, which was consistent with the tethersonde profile downwind from the tower. A sudden temperature jump of ~3°C occurred at 3 m level around 0945 CST, while a more substantial increase of 4–7°C occurred later at the two upper levels. Video filmed from a nearby tower during the burn suggested that the early increase at the 3 m level was due to the initial back burn at the tower's periphery, while the more significant increase in temperature at upper levels corresponded to the main fire plume impinging on the tower minutes after the northern edge of the prairie was ignited. This same pattern was seen in the mixing ratio values for each level. The initial, near-surface plume from the back burn produced a small spike in mixing ratio at 3 m around the same time as temperature at the 3 m level increased suddenly. More significant increases in water vapor mixing ratio of 0.5–1 g $kg^{-1}$ occurred at the higher levels later, as the main plume passed the tower. The larger increases in both mean temperature and mixing ratio observed later were due to the larger burn area and higher burn intensity, which produced a taller and more intense plume. Wind speed increased with height before and after the burn, as would be expected. But when the tower intercepted the main plume, the wind speed at the three levels converged, suggesting enhanced turbulent mixing by the fire.

Significant increases in the turbulent fluxes due to the fire plume are clearly illustrated in the time series plot in Fig. 5. Values of $CO_2$ flux increased from −0.08 mg $m^{-2}$ $s^{-1}$ to 171.0 mg $m^{-2}$ $s^{-1}$. Sensible heat flux increased from 38.4 W $m^{-2}$ to 1183.5 W $m^{-2}$ and latent heat flux increased from 29.7 W $m^{-2}$ to 376.6 W $m^{-2}$. An examination of time series plots of the high-frequency data (Fig. 6) between 0930 and 1100 CST revealed a clear distinction between small plumes passing the tower during the back burn (i.e. 0945 and 0948 CST) and the main head fire plume passing at ~1019 CST, with temperatures increasing from 14°C to a maximum of ~34°C. Increases in both $H_2O$ and $CO_2$ concentrations correlated well with the temperature increases, indicating these observed spikes were smoke plumes. During the entire burn period, including the back-burning around the tower base, $CO_2$ concentration increased from ~378 parts per million by volume (ppmv) to over 2560 ppmv, while water vapor

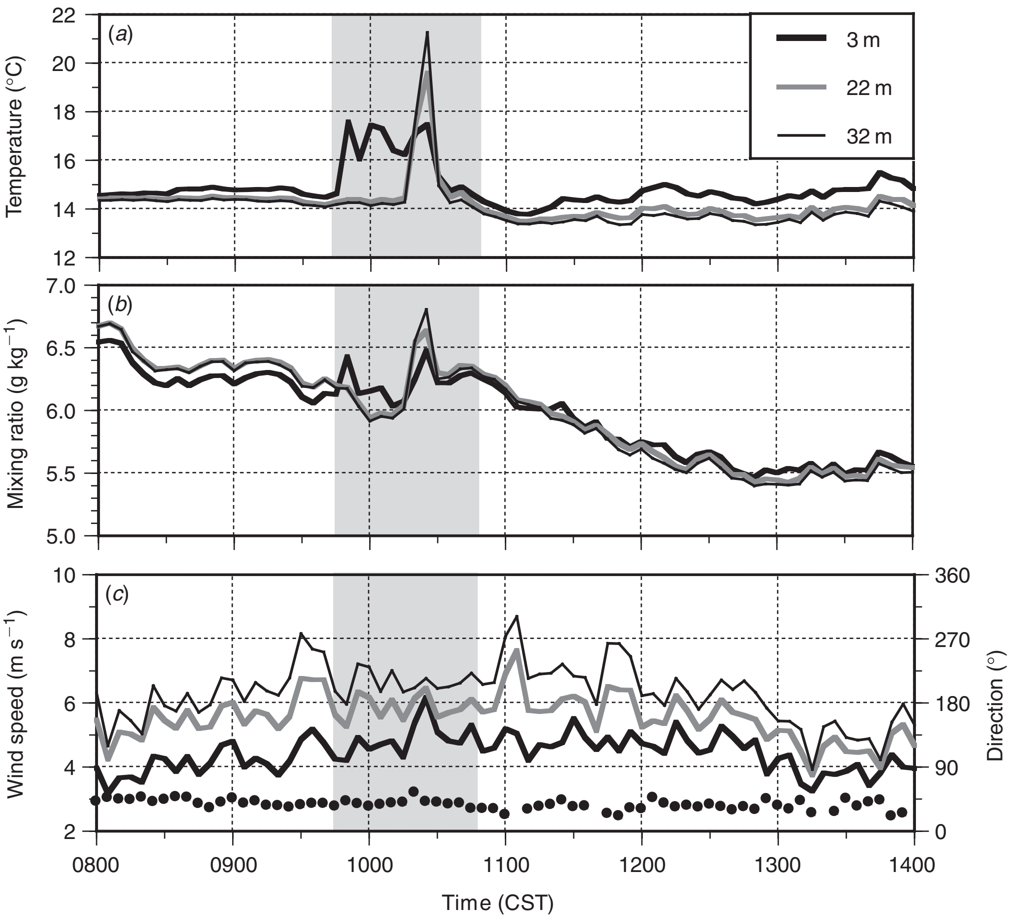


**Fig. 4.** Time series of 5-min averaged (*a*) temperature, (*b*) water vapor mixing ratio, and (*c*) wind speed at three heights (3 m, 22 m, and 32 m) on the tower. Wind direction is indicated by the dots in (*c*) for the 3-m level.

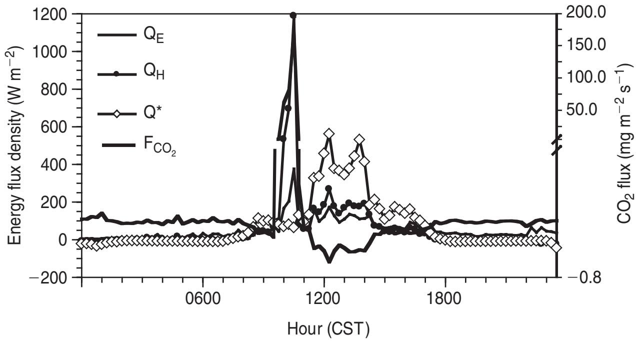


**Fig. 5.** Time series of 15-min mean turbulent fluxes of energy (Q*, net radiation; $Q_H$, sensible heat; and $Q_E$, latent heat) and $CO_2$ ($F_{CO_2}$) during the fire.

mixing ratio increased from $\sim$6.9 g kg$^{-1}$ to 9.08 g kg$^{-1}$, an increase of 2.18 g kg$^{-1}$.

Turbulent mixing was significantly enhanced due to the intense heating of the fire. The 5-min averaged turbulent kinetic energy:

$$TKE = 0.5[\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}], \qquad (1)$$

calculated using the variance of the three wind components from the 10 Hz sonic data, is shown in Fig. 7*a*. Before the main plume of the fire impinged the tower, *TKE* varied between 1 and 2 m$^2$ s$^{-2}$, but once the tower was engulfed in the main plume at 1025 CST the *TKE* increased to $\sim$2.5 m$^2$ s$^{-2}$. *TKE* can be generated either by mechanical mixing associated with vertical wind shear or by mixing associated with buoyant thermals. While winds were relatively strong during the entire period and turbulence was generated by vertical wind shears, the increase in *TKE* when the main plume passed the tower was more likely to be caused by buoyancy rather than by mechanical mixing because the wind shear was significantly reduced, as indicated by the converging wind speeds at the three levels on the tower (Fig. 4*c*).

Another method to determine the turbulent nature of the fire plume is to examine the flux Richardson number ($R_f$),

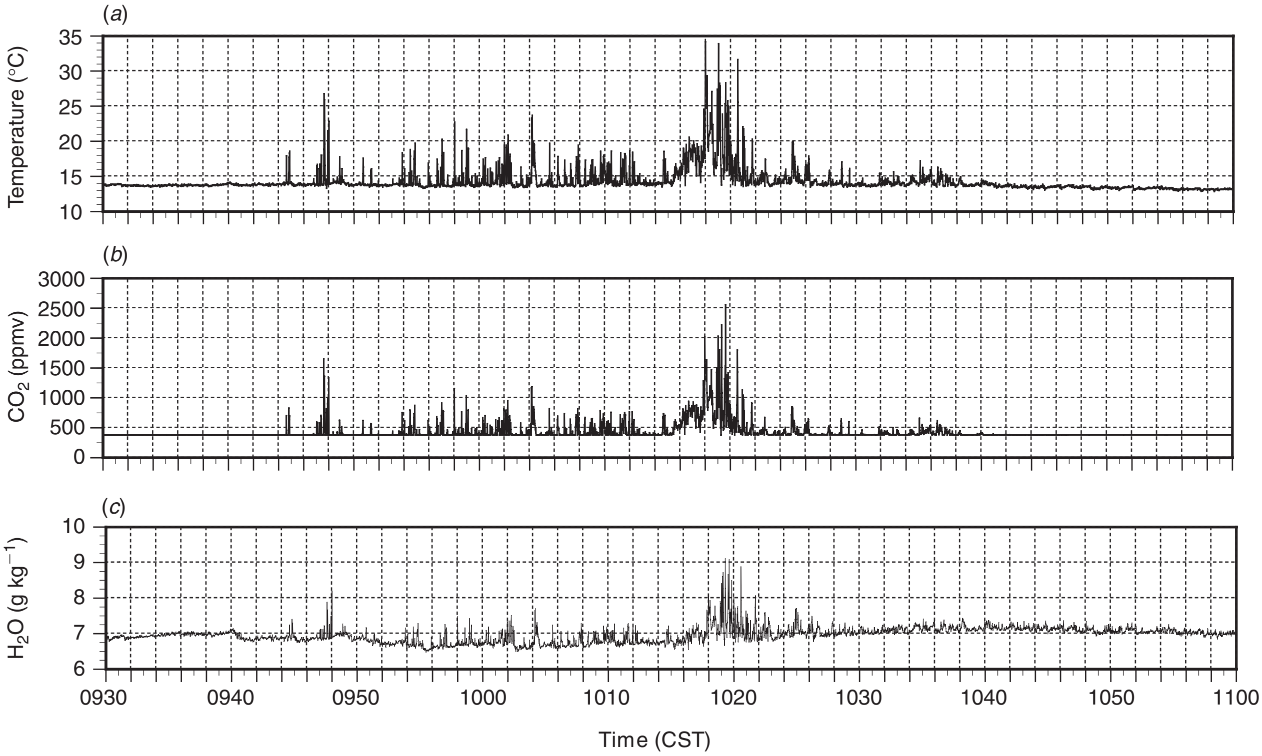


**Fig. 6.** Time series of 10-Hz turbulent quantities averaged to 1 s during the fire. (*a*) Temperature, (*b*) $CO_2$, and (*c*) $H_2O$.

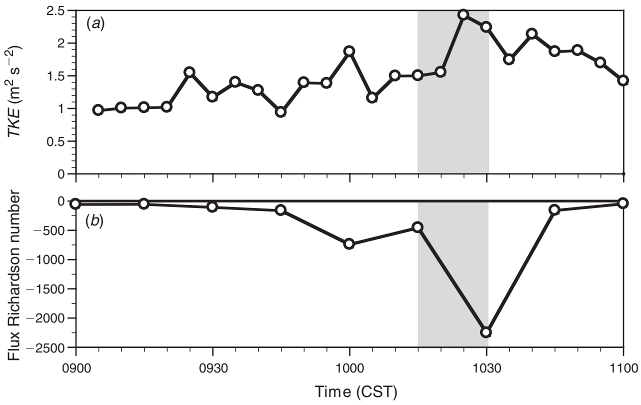


**Fig. 7.** Time series of (*a*) 5-min averaged turbulent kinetic energy and (*b*) 15-min averaged flux Richardson number. Gray shading indicates time of main head fire passing tower.

which is given by (Stull 1988):

$$R_f = \frac{\frac{g}{\overline{\theta}_v}(\overline{w'\theta'_v})}{(\overline{u'w'})\frac{\partial \overline{U}}{\partial z} + (\overline{v'w'})\frac{\partial \overline{V}}{\partial z}}, \tag{2}$$

where the numerator is the buoyancy production of *TKE* and the denominator is the negative of the *TKE* shear production. $R_f$ is a measure of dynamic stability: when $R_f < 1$, the flow is dynamically unstable and is turbulent; when $R_f > 1$, the flow is dynamically stable. The turbulent heat flux $(\overline{w'\theta'_v})$ and momentum fluxes $(\overline{u'w'})$, $(\overline{v'w'})$ were calculated directly from the 10 Hz sonic anemometer data and the mean vertical gradients in wind-speed were computed from the 5-min mean data from the 3 m and 22 m levels on the tower. Figure 7*b* shows the time series of $R_f$ for the period of 0900 to 1100 CST. There was an overall decrease in $R_f$ values for the period that correlated well with the increase in *TKE*. The decreasing $R_f$ indicated that the flow was becoming increasingly more dynamically unstable as values became increasingly more negative. The largest negative values occurred just after the plume had passed (∼1030 CST), indicating strong turbulence generated by the main plume.

## Theoretical comparisons

A simple bulk aerodynamic model (Potter 2003) provides a first-order estimate of the amount of water vapor one would expect as a combustion by-product from a fire such as this. This model simply determines the mass flux of water into the air and, based on wind speed and estimated vertical mixing depth, relates that water flux to the volume of air it enters. Assuming uniform mixing in the vertical and a linear fire that is much longer perpendicular to the direction of fire spread than the depth of the air layer involved, the change in mixing ratio due to complete combustion is:

$$\Delta q_v = 100\frac{fu_f(0.56 + M)}{H_M(u - u_f)}, \quad (3)$$

where $\Delta q_v$ is the change in mixing ratio (stated as mass of water vapor per mass of dry air, in $\text{g kg}^{-1}$ here); $u$ is the horizontal environmental wind speed ($\text{m s}^{-1}$); $u_f$ is the rate of fire's spread ($\text{m s}^{-1}$); $M$ is the fractional moisture content of the fuel (kg of water per kg of oven-dry fuel weight); $f$ is the fuel load ($\text{kg m}^{-2}$); and $H_M$ is the vertical plume thickness (m). The constant value of 0.56 represents the ratio of the mass of water produced by combustion of dry plant tissue to the mass of the plant tissue (Johnson and Miyanishi 2001). For this equation, we have assumed that the density of air is $\sim 1\ \text{kg m}^{-3}$.

Based on standard fuel models used in fire behavior analyses (Anderson 1982), the short grass at the study site is represented by a fuel load ($f$) of $\sim 0.16\ \text{kg m}^{-2}$. Using the fire behavior analysis program BehavePlus version 2.0 (Andrews *et al.* 2005) and the prevailing conditions at the site, we have estimated that the mean winds were $\sim 5\ \text{m s}^{-1}$, dead-fuel moisture ($M$) was $\sim 0.08$, and maximum fire-spread rate ($u_f$) was $1.1\ \text{m s}^{-1}$.

The tethersonde data showed water vapor mixing ratio increased coincident with temperature increases. The data also suggested that, ignoring the apparent undisturbed layer at 20 m, the plume was $\sim 10$ m in vertical thickness as it passed the tethersonde instruments. Using 10 m as an estimate of $H_M$ and the other values presented in the previous paragraph, the estimated water vapor mixing ratio increase from the fire based on Eqn 3 was $2.9\ \text{g kg}^{-1}$.

An idealized plume from a surface fire will rise at an angle dependent on the atmospheric stability, which will affect the ascent rate and mean horizontal winds, with greater ascent or weaker horizontal winds yielding a more vertical plume. Turbulent mixing of the plume would be greater on the downwind side. The least-diluted air would always be on the upwind side of the plume, with dilution and mixing increasing with height and distance from the upwind plume edge. Because the plume leans in the same direction it moves, it would pass over a given location (such as the instrument tower) at upper levels and gradually descend. As it approaches the location, smoke density, $CO_2$, $H_2O$, and temperature perturbations at a given height will increase. If the progress of the fire towards the location were to stop for some reason, instruments below some height may never detect the plume and lower levels might detect only diluted air, never encountering the less-diluted air on the upwind side of the plume. In the current study, the back burn around the guy wires stopped the fire's progress towards the instrument tower, prohibiting the 3 m sensors from ever detecting the plume of the main fire.

One can also perform the same bulk aerodynamic estimate and comparison with the tower data. Using the photos and video recording of the tower during the fire, we could estimate that the plume thickness, $H_M$, at 1025 CST was between 10 and 15 m. The average wind speed for the 22 m and 32 m levels at 1025 CST was $6.6\ \text{m s}^{-1}$. These values, with the same rate of spread and fuel-load values as earlier, yielded an estimated mixing ratio perturbation of $2.0\ \text{g kg}^{-1}$ (for a 10 m-thick plume).

The above estimates based on the simple aerodynamic model are limited by the accuracy of the parameters in Eqn 3. For example, the rate of spread ($u_f$) is an estimated maximum. If the real rate were lower – which may be a fair assumption, given the wet-field conditions – then the perturbation moistures would be lower, and the calculations would agree better with observations. Furthermore, air density on this day was probably closer to $1.2\ \text{kg m}^{-3}$ as $P = 1020$ mb and $t = 15°\text{C}$, which may also cause a lower $q_v$ estimate. Finally, the fuel load is an estimate that would also have an impact on the estimated $q_v$ value.

In order to compare the prescribed fire in this study to other wildland fires, fire-line intensity was estimated. Following Byram (1959), fire-line intensity is the rate of heat-release per unit length of a flaming front ($\text{kW m}^{-1}$) and is defined as:

$$I \equiv Hwr, \quad (4)$$

where $H$ is fuel heat of combustion ($20\,000\ \text{kJ kg}^{-1}$), $w$ is the weight of fuel consumed per unit area in the active flaming zone ($\text{kg m}^{-2}$), and $r$ is the rate of spread ($\text{m s}^{-1}$). Starting with the average low heat of combustion, $H$ was reduced by $1400\ \text{kJ kg}^{-1}$ (the latent heat of vaporization required for the water produced during complete combustion) and $200\ \text{kJ kg}^{-1}$ to account for the fuel moisture content that was estimated to be 0.08. Applying the reduced heat of combustion ($18\,400\ \text{kJ kg}^{-1}$) to Eqn 4 with $w = 0.16\ \text{kg m}^{-2}$ and $r = 1.1\ \text{m s}^{-1}$, fire-line intensity is calculated to be $3240\ \text{kW m}^{-1}$. This intensity may be an overestimate because the estimated spread rate chosen may have been lower. However, Noble (1991) found fire-line intensities for a very fast-moving ($6.4\ \text{m s}^{-1}$) and intense grassland fire to be on the order of $20\,000\ \text{kW m}^{-1}$. While the fire described by Noble (1991) is extreme, other fire-line intensities have been reported by Budd *et al.* (1997) and indicate that $3200\ \text{kW m}^{-1}$ is reasonable for our estimated parameters.

## Conclusions

We have presented *in situ* measurements of heat, water vapor, and $CO_2$ fluxes during a prescribed prairie fire located near the Texas Gulf Coast using instruments mounted on a 43-m micrometeorological flux tower within the prairie fire and a tethered balloon sounding system immediately downwind of the fire. The observations showed, as expected, a dramatic increase of mean (up to 7°C) and instantaneous (as much as 20°C) temperature, sensible heat fluxes ($>1000\ \text{W m}^{-2}$), and $CO_2$ concentration ($>2000$ ppmv) associated with the passage of fire plumes, as well as an intensification of turbulent mixing within the plumes. In addition, both the tower and the tethersondes revealed a significant increase in water vapor mixing ratio of $\sim$1–2 g $kg^{-1}$ in the fire plume. This observed increase in water vapor amount is in good agreement with theoretical estimates using a simple bulk aerodynamic model and confirms Potter's (2005) theoretical argument that a wildland or grass fire may add 1–5 g $kg^{-1}$ of water vapor to plume air.

Although the dataset was limited to one fire, the results suggest that the release of water vapor to the atmosphere, together with the temperature perturbation produced by the heat release from a landscape fire, can significantly modify the dynamic environment of the lower atmosphere. Considered along with the results of Achtemeier (2003) and the Project Flambeau results (Countryman 1969), this study shows that such moisture enhancement occurs in plumes produced by fires with scales from 1 m or so to over 100 ha.

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