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Research Note

The effect of sampling rate on interpretation of the temporal characteristics of radiative and convective heating in wildland flames

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Abstract. Time-resolved radiative and convective heating measurements were collected on a prescribed burn in coniferous fuels at a sampling frequency of 500 Hz. Evaluation of the data in the time and frequency domain indicate that this sampling rate was sufficient to capture the temporal fluctuations of radiative and convective heating. The convective heating signal contained significantly larger fluctuations in magnitude and frequency than did the radiative heating signal. The data were artificially down-sampled to 100, 50, 10, 5 and 1 Hz to explore the effect of sampling rate on peak heat fluxes, time-averaged heating and integrated heating. Results show that for sampling rates less than 5 Hz the difference between measured and actual peak radiative heating rates can be as great as 24%, and is on the order of 80% for 1-Hz sampling rates. Convective heating showed degradation in the signal for sampling rates less than 100 Hz. Heating rates averaged over a 2-s moving window, as well as integrated radiative and convective heating were insensitive to sampling rate across all ranges explored. The data suggest that peak radiative and convective heating magnitudes cannot be fully temporally resolved for sampling frequencies lower than 20 and 200 Hz.

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Introduction

Heat transfer drives wildland fire ignition and spread (Anderson 1969; Butler *et al.* 2004; Sacadura 2005; Silvani and Morandini 2009). Radiative energy transport has received the bulk of the interest in wildland fire research, but recent studies have focussed on understanding the role of both radiative and convective energy transport to wildland fire ignition and spread (Morandini and Silvani 2010). For example, the radiometric properties of the energy emitted from wildland flames have been of particular interest (Parent *et al.* 2010) along with analysis of heat flux measurement uncertainty in flames (Bryant *et al.* 2003; Pitts *et al.* 2006). However, understanding of the properties of radiative energy transfer in wildland flames is still limited (Sacadura 2005; Viskanta 2008), which is likely due to logistics associated with sensor deployment, the high temperature environment and the natural variability in fire intensity over time and space. Similar needs and data paucity exist in relation to convective energy transport. When considering relationships between energy transport in wildland flames and particle ignition it is unclear how small particles respond to temporal fluctuations in the heating source. An analytical solution to small particle heating (Frankman 2009) demonstrates that particle time to ignition is related to both the periodicity and the magnitude of the heating source. It also shows that these two factors are directly correlated (i.e. lower frequency signals result in ignition at lower magnitudes). Thus the temporal characteristics of the heating regime are relevant to additional understanding of wildland fire. No previous studies have evaluated time-resolved radiative and convective heat flux measurements from wildland fires in the context of the effect of finite sampling rates on the interpretation of peak, time-averaged and integrated radiative and convective heating rates. For this study time-resolved heat flux data from two different locations and times in the same prescribed fire event were collected. They are grouped into a low intensity set (hereafter labelled Burn 1) and a moderate intensity set (hereafter labelled Burn 2). Both sets were evaluated to determine the effect of sampling rate on the interpretation of convective and radiative heat fluxes. Findings from the analyses have direct application to measurement methods and interpretation of energy transport measurements in wildland fires.

Method

The test area was a 36-ha prescribed burn unit in western Montana (location 45°55′8.4606″N, 113°44′35.2788″W) in ponderosa pine (*Pinus ponderosa* C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest fuels, ignited

2 October 2008. The site has a south-east aspect and an elevation of 1518 m. Air temperature and relative humidity at the time of the burn were nominally 23°C and 20%.

The convective and radiative heat flux sensors were placed in the path of heading fires in two distinct fuel types resulting in two contrasting fire intensities. The fuels in Burn 1 were dominated by forest grasses with minimal conifer litter resulting in low fire intensity and are best described by a grassland fire behaviour fuel model GR1 (Scott and Burgan 2005). The terrain slope in this area was nominally 10% and 30-s average winds were low ($\sim$0.5 m s^{-1}) as determined from onsite estimation. Flame heights in Burn 1 were nominally 0.3 m, rate of spread was 0.042 m s^{-1} and flame residence time was 5 to 7 s as determined from ocular estimates of videos of the fire. The moderate intensity Burn 2 resulted from a modest concentration of woody fuels that are best described as a slash–blowdown fire behaviour model SB1 (Scott and Burgan 2005). Slope in this area was steeper (nominally 20%) and winds had increased to 1.5 m s^{-1}. Flame heights averaged 0.8 m, rate of spread 0.167 m s^{-1} and flame residence time was 30 s as determined from ocular estimates of video images of fire burning near the sensors. Vegetation consumed in the flaming front was 0.1 kg m^{-2} in Burn 1 and 1.1 kg m^{-2} in Burn 2 as estimated from ocular comparisons against past burns and derivations from representative fuel models. No fuel moisture measurements were collected. The sensors were positioned $\sim$0.3 m above the ground and were facing downhill and into the wind such that the head fire would spread directly towards them.

Time-resolved convective and radiative heat fluxes were measured simultaneously using a dual-sensor configuration. The sensor system consisted of two HFM 7 heat flux microsensors (Vatell Corp., see http://www.vatell.com/hfm.htm, accessed 20 August 2012) mounted side by side in an insulated aluminium block nominally 10 by 10 by 20 cm in size. A 0.5 mm-thick sapphire window was mounted over one of the two sensors with a 0.5-mm air gap between window and sensor, whereas the other sensor was left exposed. The field of view of both sensors was the same and was a cone of rotation prescribed by a 160° subtended angle. Both sensors were mounted with the active surfaces oriented vertically so as to detect incident heat transfer from the incoming horizontal direction. The surface of the windowed sensor was continuously purged with air to prevent fouling by soot or other combustion by products. The non-windowed sensor gathered total (convective plus radiative) heat transfer whereas the windowed sensor gathered only radiative energy (after some quantified and corrected loss in transmission through the window). The thermal mass of the mounting apparatus and thermal insulation prevented the sensor temperature from rising more than 6°C above ambient during the burn events reported here. The measurement system, methods and calibration procedure are described in further detail elsewhere (Frankman 2009; Frankman *et al.* 2012). Convective and radiative heat fluxes are defined as a flow of energy per unit time through a unit area. For this analysis the focus was on the temporal nature of the signals rather than the absolute values. Thus, absolute measurement accuracy was less critical than relative accuracy. Nonetheless the measurements are likely to be accurate for the sensor configurations employed. Absolute measurement uncertainty was estimated to be less than 8% (Bryant *et al.* 2003) and was measured to be much closer to 2% during the primary heating periods (Frankman *et al.* 2012).

Results and discussion

With greater fuel loading and longer-burning fuel characteristics, the overall intensity of Burn 2 was greater than that of Burn 1. Despite the radiative and convective heat flux magnitude differences between the two sets of measurements, they exhibited similar temporal characteristics.

Fig. 1 presents time histories of heat fluxes measured in Burn 2. To determine the effect of sampling rate on the measured heat flux the data originally sampled at 500 Hz were down-sampled to five arbitrary lower sampling rates (100, 50, 10, 5 and 1 Hz). For example, to simulate a 50-Hz sampling rate, every 10th data point in the 500-Hz series was sampled. Likewise, to simulate a 10-Hz sampling rate, every 50th point was sampled. In all cases, the down-sampled time series used the same starting time. Fig. 1*a* presents the original 500-Hz data. Fig. 1*b–f* presents the data down-sampled to 100, 50, 10, 5 and 1 Hz. The inset figures highlight the data at each respective sampling rate over a 3-s time period centred at or near ignition associated with flame arrival ($\sim$70.6 s as indicated by the rapid rise in radiative flux signal of Fig. 1*a*). The flame arrival is preceded by several short duration but high magnitude convective pulses. The radiative heat flux in this burn event peaks at 50.3 kW m^{-2} and the convective heat flux peaks at 109.9 kW m^{-2}. The radiative heat flux exhibits significantly lower amplitude temporal fluctuations than the convective signal which is characterised by short duration, large magnitude positive (heating) and low magnitude negative (cooling) pulses.

Table 1 presents a summary of key characteristics of the data. Visual inspection of Fig. 1*b* indicates that for a down-sampled rate of 100 Hz there appears to be some degradation of the convective flux signal, particularly in the peak magnitudes. It is not clear if the radiative signal is affected. Table 1 indicates that for Burn 1 the radiative peak flux is virtually unchanged from 500 to 100 Hz, but the peak convective flux decreases from 64.1 to 52.8 kW m^{-2}. For Burn 2 both the convective and radiative signals are essentially unaffected by down-sampling to 100 Hz. At 50 Hz the peak radiative magnitudes remain largely unaffected, but peak convective fluxes were reduced to 40 kW m^{-2} for Burn 1 and 96 kW m^{-2} for Burn 2, and further, some of the convective pulses are lost (as indicated by Fig. 1*c*). This is not surprising, since the power spectra for both burns (not shown here) reveal frequency content in the radiative heat flux fluctuations ends just above 10 Hz (Frankman 2009). Degradation of the radiative heat flux signal is first detectable at a down-sample rate of 10 Hz in both burns and convective flux values continue to be reduced significantly. Finally, at a down-sample rate of 1 Hz the characteristic rapid fluctuations in the convective heat flux are lost (Fig. 1*f*), and radiative flux peaks are reduced to nominally 60% of the full magnitude values whereas convective peak fluxes are reduced to 50 and 30% of the peak values for Burn 1 and 2. At this sampling rate the convective heat flux peaks are lost and radiative heat transfer appears to be dominant from the peak heating point of view.

The data and analysis suggest that convective heating is characterised by high-frequency and high-magnitude

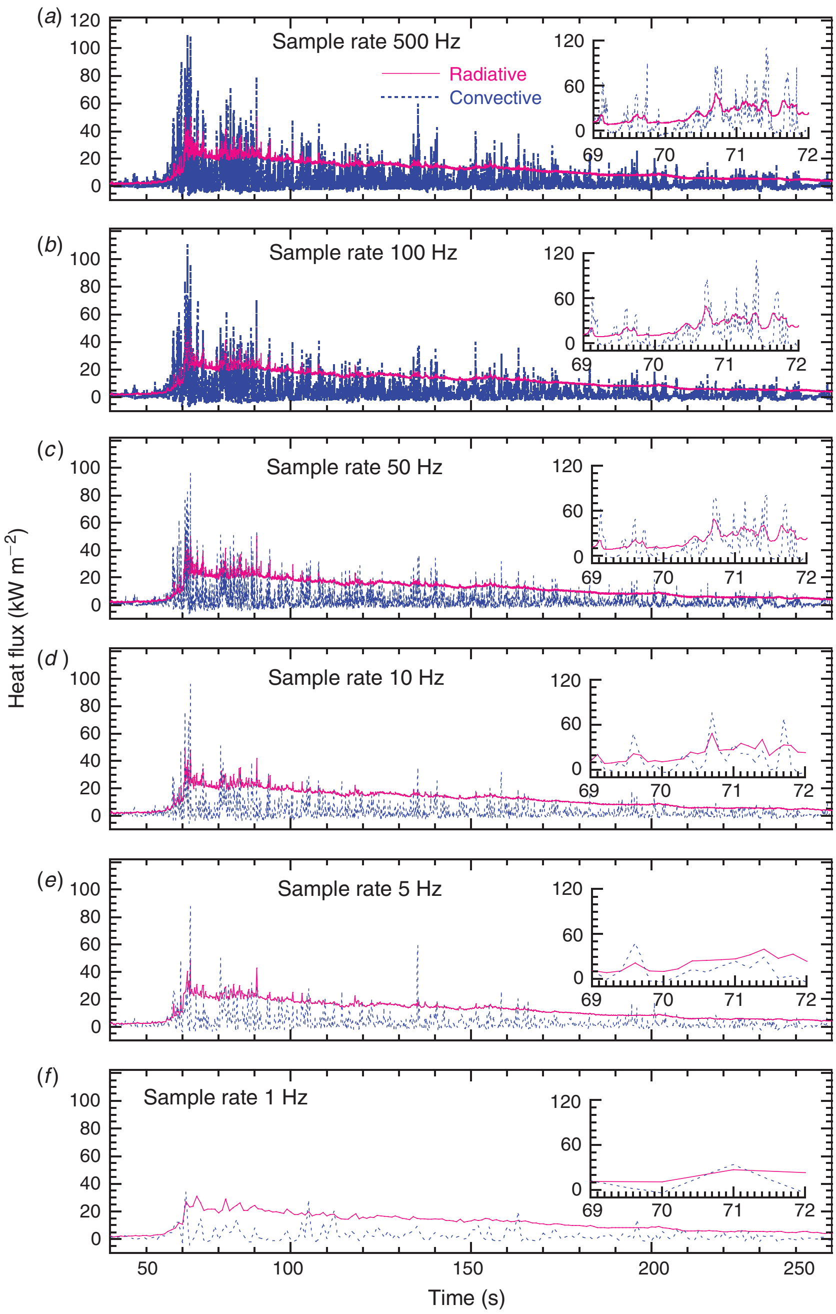

Fig. 1. The effect of sample rate on measured heat flux in Burn 2. (*a*) presents the initial signal captured at 500 Hz, (*b*) presents the 500-Hz signal down-sampled to 100 Hz and so on to 1 Hz for (*f*). The inset figures depict the signal over a 4-s time period centred at or near ignition.

fluctuations up to 100 Hz whereas radiative heating is limited to fluctuations less than 10 Hz. The peak magnitude of the convective heating is substantially greater (i.e. two to three times) than the radiative heating. These findings are supported by Clark and Radke (1999) who show the existence of small turbulent structures within flames using infrared imagery and postulate that these structures replicate convective heat transfer.

The Fire Radiative Energy (FRE) has been shown to relate directly to fuel consumption (Wooster *et al.* 2005; Freeborn *et al.* 2008). We introduce a related term, Fire Convective Energy (FCE), which is the integral of the convective heat fluxes, and explore the effect of sampling rate on FRE and FCE as energy densities or fluxes. The results of the integration are shown in Fig. 2*a* for Burn 2 at all frequencies (1, 5, 10, 50, 100, 500 Hz). As the combustion event commenced, the cumulative radiative flux began to rise first due to preheating by the approaching flame. Although some convective cooling of the radiatively preheated sensors before arrival of the flame front

Table 1. Peak radiative and convective heat flux resolved for the two burns as a function of sampling rate

Sampling rate (Hz)	Burn 1				Burn 2			
	Peak radiative flux ($kW\,m^{-2}$)	Peak convective flux ($kW\,m^{-2}$)	Fire radiative energy ($kJ\,m^{-2}$)	Peak (2 s) smoothed radiative flux ($kW\,m^{-2}$)	Peak radiative flux ($kW\,m^{-2}$)	Peak convective flux ($kW\,m^{-2}$)	Fire radiative energy ($kJ\,m^{-2}$)	Peak (2 s) smoothed radiative flux ($kW\,m^{-2}$)
500	22	64	302	11	50	110	3052	31
100	22	53	302	11	50	110	3050	31
50	22	40	302	11	50	96	3050	31
10	17	41	301	11	49	96	3050	30
5	17	41	300	11	48	88	3050	30
1	12	21	295	10	31	34	3008	27

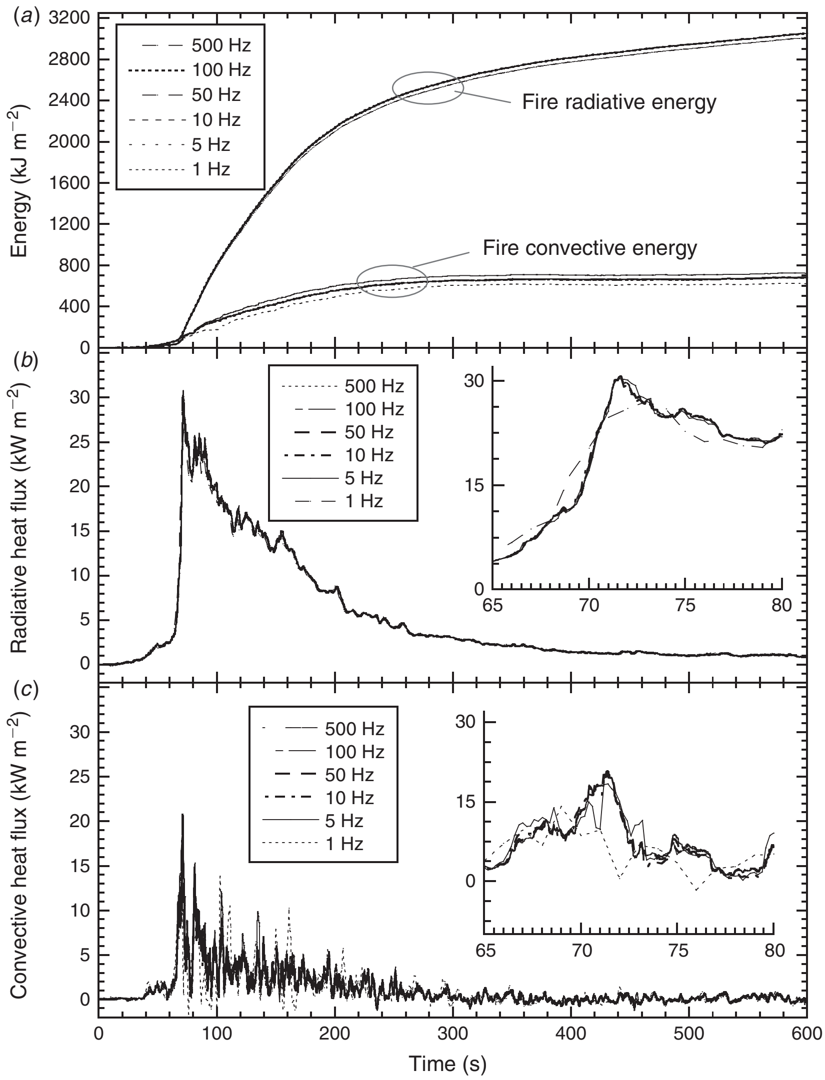

Fig. 2. Integrated energy and 2-s moving averages for Burn 2. (*a*) Fire radiative energy and convective energy calculated from integral of measured fluxes, (*b*) fluxes calculated using a 2-s moving average of the 500-, 100-, 50-, 10-, 5- and 1-Hz radiative flux signals, (*c*) fluxes calculated using a 2-s moving average the 500-, 100-, 50-, 10-, 5- and 1-Hz convective flux signals. Inset figures in (*b*) and (*c*) are included to further illustrate the difference in signal between the moving averages of the various sample rates over a short time frame.

was observed in the data from Burn 1 (not shown), from ignition onward both the cumulative radiative and convective energy rise until the combustion event is over for both datasets. Comparison of the cumulative flux histories calculated from the six sampling rates indicates that FRE and FCE may be resolved with little loss in accuracy even at 1 Hz. In fact, the cumulative heat flux histories corresponding to the different down-sampling frequencies are difficult to distinguish from one another except for the slightly lower value (e.g. a nominally 8% decrease) of FCE at the 10-, 5- and 1-Hz rates. Thus, although high-frequency sampling is necessary to capture rapid temporal fluctuations and accurately resolve peak values, the cumulative heating load is dominated by longer-duration heating events in the record and can be measured at considerably lower sampling frequencies. This is especially true for radiative heating.

A 2-s moving average heat flux was calculated for every time (t) in the dataset (Fig. 2*b* is radiative heating and Fig. 2*c* for convective heating). Comparison of the 2-s moving average at the different sample rates reveals that it can be reproduced with little loss in accuracy to 5 Hz. The inset time histories shown for the 15 s time period suggest that slight degradation in the signal occurs at 1 Hz. Clearly the moving average is dominated by longer-duration events than are the short-pulse peaks seen in the high-frequency time series.

The effect of sensor time response is not considered in the down-sampling analysis. The sensors used in this analysis had a time constant of 300 μs. Generally, it is accepted that a period of five time constants is sufficient to capture a signal to greater than 99% accuracy (Beckwith *et al.* 1982). Thus, the response of the sensors used here was sufficient to capture signals occurring with frequency content less than 666 Hz. Lower sensor time response may act effectively as a low-pass filter and negate the capability to resolve magnitudes and temporal properties of the signal at sampling rates higher than the frequency response of the sensor.

The implication of these data is that for sampling frequencies from 1 to 10 Hz caution should be exercised when interpreting peak radiative fluxes as it is likely that the actual peaks are not resolved. Caution should also be exercised in the interpretation of convective *v.* radiative heating rates as convective heating fluctuations occur at much higher frequency than radiative heating and, depending on fire conditions, sometimes exhibit much greater amplitudes. However, for the most part it appears that average values and cumulative energy loads based on 1-Hz sampled data are representative of those captured at higher rates. For cases where the objective is to characterise the temporal properties of the signal the minimum sampling rate should consider aliasing. Signal processing theory identifies the minimum frequency that can be resolved accurately as being one-half the sampling rate (Shannon 1949; Blackledge 2003). Therefore, the data and analysis presented here imply that minimum sampling rates required to resolve temporal fluctuations in radiative energy heating should be above 20 Hz (to resolve 10-Hz fluctuations) and above 200 Hz (to resolve 100-Hz fluctuations) for convective heating.

Conclusions

The analysis presented here has significant implications for interpretation of radiative and convective heating measurements in wildland flames. The results are based on the temporal response of the sensors and are independent of the absolute measurement accuracy. Peak heating magnitude measurement uncertainty can be large for sampling rates less than 20 Hz for radiative heating and less than 200 Hz for convective heating. However, the analyses also indicate that integrated and time-averaged values are valid even for sensor sampling rates as low as 1 Hz. Of the two datasets collected, the more intense burn event exhibited slightly higher frequency content. Although it appears that higher sampling rates are required to fully capture heat transfer in wildland fires the instantaneous cumulative heat flux and a moving average may be captured at a much lower frequency. It is acknowledged that even more intense combustion events such as brushfires or crown fires may have higher frequency content than is represented here. However, it is also possible that the longer burning duration associated with larger-size flames (i.e. longer duration residence times) could actually reduce the fluctuations in the heating signal. Clearly additional studies are warranted to extend the observations presented here to a broader range of fire conditions.

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