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IMPACT OF SAVANNA FIRE SCARS ON HEAT AND MOISTURE FLUXES TO THE ATMOSPHERE AND FEEDBACKS TO THE LOCAL BOUNDARY LAYER.

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1. INTRODUCTION

The far north of Australia is dominated by tropical savannas and subject to frequent yet non-destructive burning of the grassy understorey. Each year within northern Australia, huge tracts of savanna are burnt (~250,000 km^2), with this area likely to increase under predicted climate change (Williams *et al*., 2001). Caused mainly by pastoralists, Aboriginal landholders and conservation managers, as well as by lightning strikes (Russell-Smith *et al*., 2000; Williams *et al*., 2002), this frequent burning is thought to be the greatest natural and anthropogenic environmental disturbance within this extensive ecosystem (Russlel-Smith *et al*., 2000). Fire can influence climate both directly and indirectly. Direct effects occur through the emission of smoke and trace gases from the burning and combustion of fuels. Indirect effects occur via fire and subsequent fire scars and are likely to radically alter surface properties and the surface energy budgets, which form important feedbacks to the atmosphere (Beringer *et al.,* 2003).

Fire scars, which refer to the charred and blackened landscape after a fire event, can radically alter the surface energy budgets by reducing surface albedo, increasing available energy for partitioning into convective fluxes and increasing substrate heat flux. These changes affect surface-atmosphere coupling and have the potential to influence atmospheric motion and moist convection at a range of scales. This study is an initial investigation into the effect of fire scars on the boundary layer and forms the basis for further study into the larger scale effects of tropical savanna fire scars on local to regional climate.

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2. SITE DESCRIPTION

The project field sites were located on the Gunn Point Peninsula (Burnt Site 12°29.712S, 131°09.003E and Unburnt Site 12°18.113S, 131°06.002E) approximately 35km south east of Darwin near the township of Howard Springs, in the coastal, humid zone of the Northern Territory, Australia.

Howard Springs has a mean annual rainfall of 1750mm, with approximately 95% falling during the pronounced wet season from December to March (Hutley *et al*., 2000). This is followed by an essentially rainless dry season, lasting from May to September (Taylor & Tulloch, 1985). A transitional period occurs during the months of October and November which is characterised by increases in humidity and temperature, occasional thunderstorms and the onset of canopy flushing by many of the tree and shrub species (Williams *et al*., 1997).

Daily maximum temperatures at Darwin Airport range from 30.4°C (July) to 33.1°C (October and November) (Hutley *et al*., 2000). The maximum and minimum temperatures have a range of 7°C in the wet season and 11°C in the dry season (McDonald & McAlpine, 1991).

The vegetation of Gunn Point Peninsula consists of Eucalypt-dominated woodlands, open forests, closed forests and seasonally flooded swamps and wetlands (Hutley *et al*., 2000). The burnt and unburnt sites consist primarily of Eucalypt open forest vegetation and are typical of the tropical savannas of Northern Australia. A previous study by Hutley *et al*., (2000) at the same site showed there are approximately 600-750 stems per hectare, with *Eucalyptus tetrodonta* and *Eucalyptus miniata* the dominant species, accounting for approximately 80% of total basal area and 50% of the total canopy cover in the region (Hutley *et al*., 2000). O'Grady *et al*., (1999) also recorded that overstorey LAI varies seasonally and ranges between 0.6 in the dry season to 0.95 in the wet season for the same region.

The understorey at both sites consisted of a mosaic of small trees and shrubs with a seasonally continuous cover of annual grasses, with some perennial grasses also present (Hutley *et al*., 2000). Probably of most significance to this study is the presence of the C_4 grass *Sorghum* during the wet season. Hutley *et al*., (2000) showed that at ground level *Sorghum* spp. is responsible for a dramatic change in LAI, from a wet season value of 2-3 to a dry season value of 0.2, when the grass senesces. It is the abundance and annual drying out of the *Sorghum*, along with the presence of coarse woody debris that creates the available fuel to drive many of the wildfires in the area.

The soils of the region are generally extensively weathered and laterised, weakly acidic and low in nutrients. A detailed description of the soils can be found in (Cole, 1986; Pidsley *et al*., 1994; Cook *et al*., 1998 & Hutley *et al*., 2000).

3. FIRE SCARS

Fire scars throughout the Northern Territory can range from a few square meters to hundreds of square kilometers. The fire scar investigated in this study was centered at approximately 12°29S, 131°09E and was approximately 100km^2 in area (Figure 1). Burning occurred courtesy of a wildfire on day 241, with the fire being patchy and ranging between low (<1000 kWm^{-2}) to moderate intensity (3500 kWm^{-2}). Figure 1 shows the location and timing of fire scars in the Gunn Point region and the location of the climate/flux tower and the two tethered balloon sites.

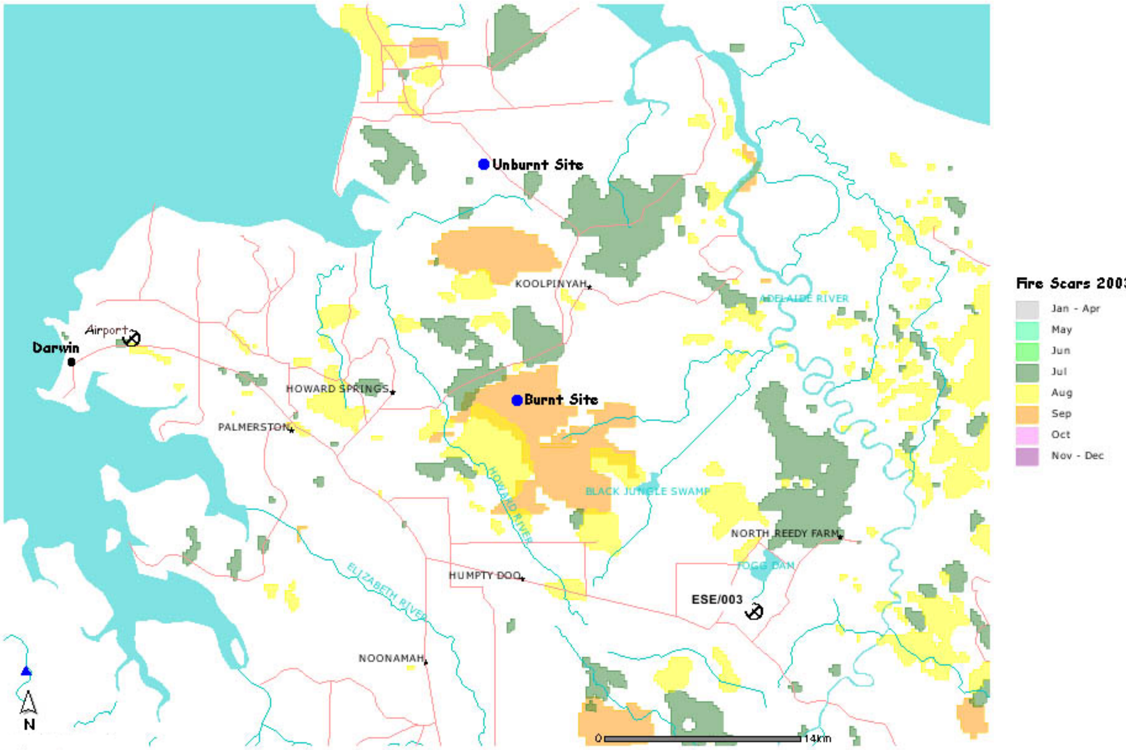

Figure 1: Location and timing of fire scars in the Gunn Point region, including the location of the experimental sites. Burnt and Unburnt sites are indicated as a blue dot. (modified from Tropical Savannas CRC map maker – North Australian Fire Information http://savanna.ntu.edu.au/information/savanna_mapmaker.html).

4. METHODS

4.1 Meteorological & Flux Measurement

An eddy covariance system was used to collect meteorological and flux data before, during and after the fire event. It has been previously described by Beringer *et al*., (2003) and will be briefly described here. A flux tower was installed approximately 10 km off Gunn Point Road (12°29.712S, 131°09.003E). The tower was 25m tall allowing measurements to be made above the canopy (canopy height of 12-14m). Sensors were positioned as close to the top of the tower as possible to maximise the surface area within the effective sensor footprint (Schmid, 1997). Three dimensional wind velocities were measured using a 3-D ultrasonic anemometer (Campbell Scientific Inc., model CSAT3) at a height of 25m and were co-ordinate rotated (McMillen, 1988). Turbulent fluctuations of CO_2 and H_2O were measured using an open path infrared gas analyser (Licor, model LI-7500). Incoming and reflected short-wave radiation were measured using a pair of pyranometers (Middleton Instruments, model EP-07) while incoming and emitted long-wave radiation were measured using a pair of pyrgeometers (Eppley Labs Inc., model PIR). Net radiation above the surface was also measured using a Frischen type net radiometer (REBS, model $Q^*7.1$) with a wind-speed-dependant dome cooling correction to applied to the results.

Soil heat flux plates (REBS, model HFT3) and soil temperature probes (Campbell Scientific Inc., model TCAV) were used to measure ground heat flux via the combination method (Fuchs & Tanner, 1968) at four representative locations. All climatic variables were measured every 10-seconds and 30-minute averages recorded to a data logger (Campbell Scientific Inc., model CR5000).

Throughout this paper all times are given as local Central Standard Time (CST = UTC

+9.5 Hours), while the term "daily" refers to the 24-h period from midnight to midnight and the term "daytime" refers to the period when net radiation is positive (10:00 – 18:00). Solar noon at Howard Springs was approximately 13:00 CST during the period of measurements. The tower data were recorded during 2003 from day 214 – 299 and split into three data blocks, pre-fire (214 240), fire (241-261) and post-fire (262-299).

4.2 Boundary Layer Measurements

Two identical tethered balloon systems were used to take vertical profiles of the boundary layer. Simultaneous soundings were taken at the burnt and unburnt site, with each system comprising a Vaisala tethered balloon, winch, radiosonde (produced by the University of Canterbury Physics & Astronomy Department) and receiving system (SALCOM, model 15-12-0000). The radiosondes recorded temperature, pressure, humidity, wind speed and direction, with the data being logged directly to a laptop using a Windows based software package (University of Canterbury). Due to the aviation operating restrictions of the area measurements were made to a maximum height of approximately 530 m above ground level. The systems were placed in the middle to downwind side of the burnt and unburnt patches in order to minimize edge effects. Each sounding took approximately 1 hour to complete. Soundings were conducted simultaneously at 01:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 at each site for days 247-249, 254-255, 261-262, 267 and 274-276. In total 172 soundings were conducted between the burnt and unburnt sites. An intensive observational day was conducted on day 267 (24/09/03) with soundings being conducted every hour between 06:00 and 21:00 and this is presented as the diurnal data set. All other data were screened, processed and combined to form single profiles for each time period. Profiles are presented here as layered height which refers to mean data in a 25 m block; for example 25 m data is the mean of all data between 0 m and 25 m, while 50 m data is all data between 25 m and 50 m.

5. RESULTS & DISCUSSION

The wildfire on day 241 of 2003 immediately affected the land surface by significantly changing the albedo. The consumption of the dry grassy understorey, coarse woody debris and the blackening of the now bare ground surface resulted in a decrease in albedo. Due to some technical difficulties albedo values for 2003 are currently unavailable. However previous studies from 2002 at the same site showed albedo almost halved from 0.12 pre-fire to 0.07 post-fire during a similar intensity late dry-season fires (Beringer *et al.,* 2003).

The heat from the understorey fire caused substantial canopy scorch and, as a result, significant leaf-drop occurred in the weeks following fire. This canopy damage was found to reduce evapotranspiration and alter the partitioning of energy from latent heating (LE) into sensible heating (H). This is best represented by the Bowen ratio (β = H/LE, Bowen 1926), with values of β near 1 indicating equal partitioning of energy as H and LE, values less than 1 indicating the majority of energy is being used in evapotranspiration and values greater than 1 indicating the majority of energy is being used for sensible heating of the surrounding atmosphere. Mean daytime β for the pre-fire period was 2.5, indicating that the majority of available energy was being dissipated via sensible heating. These values are typical of tropical savannas during the mid to late dry season, when the understorey grasses have senesced, the canopy LAI has decreased and there are low soil moisture levels (Hutley *et al*., 2000).

Fire resulted in dramatically increased daytime values of β to an average of 6.1 for the 3 weeks following the event (fire period) as the canopy was scorched and transpiration reduced to near zero. This increase in β indicated nearly 2.5 times more energy was being dissipated as sensible heating than was being dissipated by evapotranspiration (latent heating). There was also a sharp increase in β values 2 weeks after the fire (Figure 2), which is indicative of leaf fall from the dominant trees following the fire.

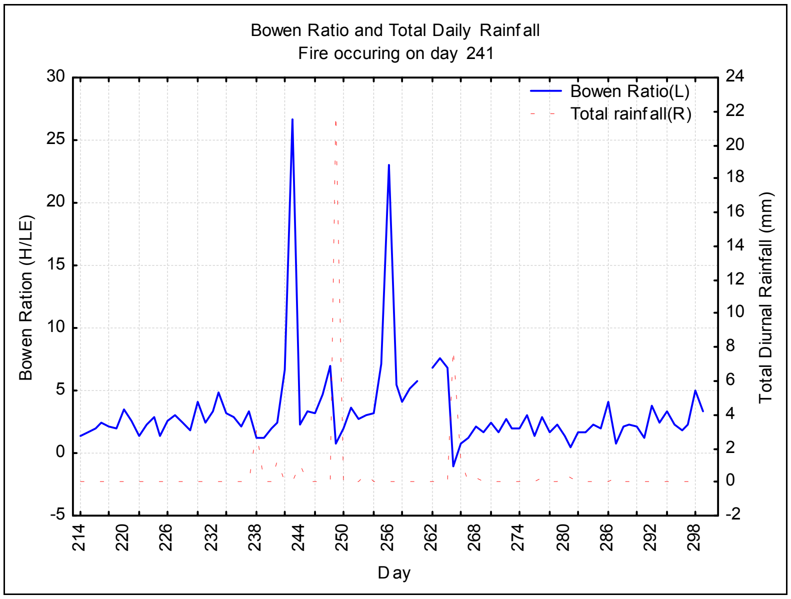

Figure 2: Pre- and post-fire Bowen ratios (□ = H/LE) and daily total rainfall (mm) for the burnt site. Fire occurred on day 241 (29th August 2003). Leaf drop is evident on day 256, while the rain events show a clear decrease in □ as evaporation is increases.

Interestingly, post-fire mean daytime β values returned to 2.5 (similar pre-fire values) more quickly than previous studies in the same area (Hutley *et al*., 2000; Beringer *et al*., 2003). Although the fire was of similar intensity to those of previous studies it was found that this recovery was due primarily to the amount of rainfall post-burn. Rainfall after the fire increased the amount of water available for evaporation and subsequently increased the amount of energy that was dissipated as latent heat, reducing the Bowen ratio. Rainfall also resulted in faster flushing of the canopy (post-fire) foliage and germination of understorey grasses, which was very obvious in the week following the fire. Soil water content, which averaged 5.1% pre-fire, increased to 6.5% during the fire period and 6.9% post-fire due to these sporadic, pre-monsoon rainfall events typical of this time of the year. Figure 3 shows a clear increase in latent heating following the increases in soil moisture due to the rainfall events.

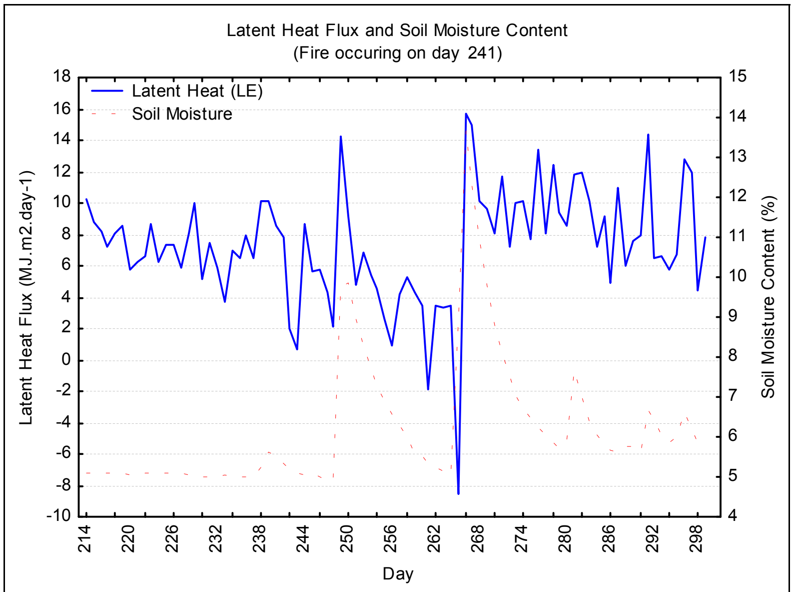

Figure 3: Daily mean soil moisture (%) and latent heating (MJ.m^2.day^{-1}) for the burnt site. Increases in soil moisture content correspond to increases in latent heating. Noting the increase in rainfall frequency results in higher soil moisture and subsequently higher latent heating of the atmosphere.

In terms of overall magnitude of the heat fluxes (Table 1), the pre-fire daily mean sensible heating was 5.94 MJ m^{-2} day^{-1} which is a moderate value due to the dry soils, low LAI, high canopy resistance and relatively high levels of incoming radiation during the day at this time of the year (Beringer *et al*., 2003). Sensible heating increased to 6.49 MJ m^{-2} day^{-1} during the fire period and again during the post-fire period to 6.92 MJ m^{-2} day^{-1}), which may indicate a seasonal trend. Latent heating was seen to decrease from 3.10 MJ m^{-2} day^{-1} pre-fire to 2.10 MJ m^{-2}d ay^{-1} during the fire period, before recovering to 3.58 MJ m^{-2} day^{-1} post-fire. The ground heat flux showed a near three-fold increase from 0.12 MJ m^{-2} day^{-1} pre-fire to 0.35 MJ m^{-2} day^{-1} during the fire period. This is a result of increased radiant load on the soil due to the significantly reduced overstorey cover because of leaf drop and because of removal of vegetation and blackening at the soil surface.

Table 1: Daily mean heat flux values for pre-fire, fire and post-fire periods.

Data Set (day)	**Sensible Heat (H)** (MJ m^{-2} day^{-1})	**Latent Heat (LE)** (MJ m^{-2} day^{-1})	**Ground Heat (G)** (MJ m^{-2} day^{-1})
Pre-Fire (214-240)	5.90	3.10	0.12
Fire (241-261)	6.49	2.10	0.35
Post-Fire (262-299)	6.92	3.58	0.36

Although not as large as previous changes reported at the same site by Beringer *et al*., (2003) (a moderate fire during 2001 resulted in a change in daily sensible heat flux of 4.9 MJ m^{-2} day^{-1} pre burn to 7.6 MJ m^{-2} day^{-1} post-burn), the changes during the 2003 fire are still evident. Even accounting for the effect of rain shortly after the fire event, the impact of fire in tropical savannas on the partitioning of energy from latent heating to sensible heating can clearly be seen to impact the overlying atmosphere.

Boundary layer profiles taken in the weeks following the fire show that the atmosphere over the fire scar is warmer and more effectively mixed. Simultaneous hourly vertical temperature profiles for the morning of day 267 (24/09/03) show that the burnt site is warmer throughout each profile to the maximum height measured (350 m to 400 m) in every case except at 08:00. At this time the two sites are almost at equilibrium (i.e. no significant difference in temperature) (Figure 4).

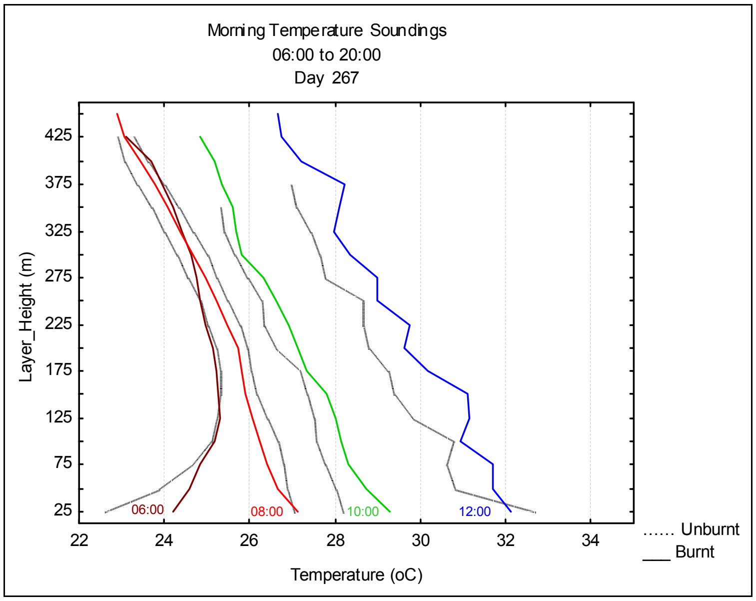

Figure 4: Morning temperature soundings for burnt and unburnt sites on day 267 (24/09/03). Soundings were conducted every hour on the hour from 06:00 to 21:00, however only every second hour is shown. Unburnt soundings are shown with and dashed line and burnt sounds with a solid line.

Interestingly, at 06:00 the near-surface (0-75 m) air temperature at the burnt site was warmer by 1.8°C when compared to the unburnt site (we might have expected the differences to disappear overnight). At heights greater than 75m, the two profiles converge. Reasons for this are not entirely clear, but may indicate enhanced heating of lower zones of the profile over the relatively cleared burnt land surface as the sun rises. However this is inconsistent with the similarity of profiles at 08:00. Conversely the fire scar may still heating the lower levels of the boundary layers as a result of increased heat retention of the blackened land surface over night, although this is unlikely and discussed later in this section.

Heating of the atmosphere by the land surface increases fairly rapidly as more solar energy is input into the system during the morning, with mean temperatures in the first 25m increasing from 22.6°C at 06:00 to 28.2°C at 10:00 and from 24.2°C at 06:00 to 29.3°C at 10:00, at the unburnt and burnt sites respectively. Although the surface temperature at the unburnt site at 12:00pm is slightly higher than at the burnt site the profile clearly shows that the burnt site is warmer throughout the entire measured profile by up 2°C at some levels. At a height of 375m the burnt site is seen to be 1.5°C warmer. This increased convection from the surface, as more energy is partitioned into sensible heating than latent heating over the burnt site (β>1, Figure 2), would produce enhanced mixing and the possible formation of a deeper boundary layer.

Heating continues throughout the day with the burnt site temperatures considerably higher than the unburnt site at both 14:00 and 16:00 (Figure 5). By 18:00 and 20:00 differences in the profiles are substantially reduced.

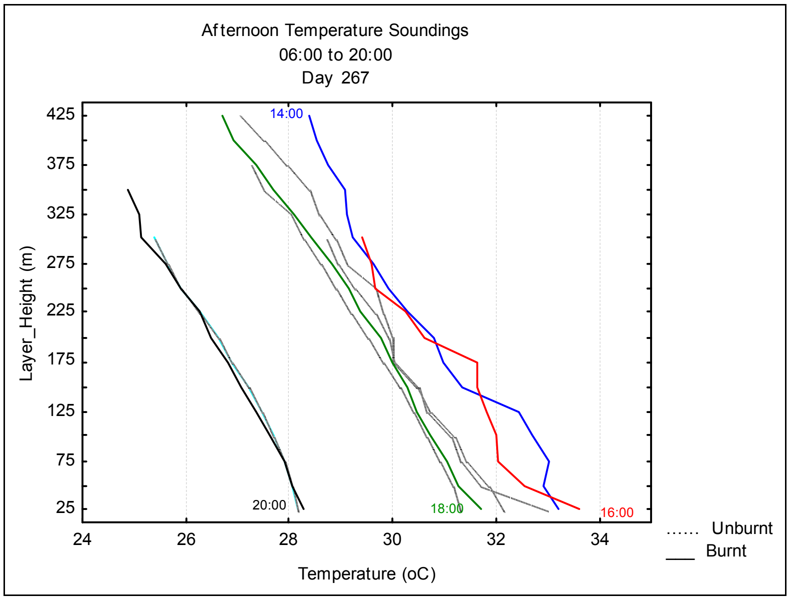

Figure 5: Afternoon temperature soundings for burnt and unburnt sites on day 267 (24/09/03). Soundings were conducted every hour on the hour from 06:00 to 21:00, with every second hour is shown here. Unburnt soundings are shown with and dashed line and burnt sounds with a solid line.

The burnt site shows a more rapid rate of boundary layer cooling between 16:00 and 18:00, indicating that once solar load decreases, the burnt surface loses heat more rapidly than the unburnt surface. This further supports the contention that the differences observed at the surface during the 06:00 sounding may be a result of more rapid heating of the burnt surface.

To investigate the effect of the fire scar over a longer time scale, individual runs for a specific time of day (e.g. all 06:00 runs) were combined and the mean taken for each 25 m layer of the atmosphere, with days being used as replicates. Analysis of these data shows that at 01:00 there is a clear temperature inversion in the first 100m at both sites (Figure 6). This is a typical nocturnal profile for a system that is characterised by clear skies, relatively high daytime surface temperatures and rapid surface cooling over night. Interestingly the burnt site was still warmer throughout the profile up to a height of approximately 300m when the two profiles converged. This indicates that surface temperatures at the burnt site at 01:00 are on average, higher than at the unburnt, and as a result there is larger sensible heating loss to the overlying atmosphere. This may also indicate that the burnt soil is storing more heat than the unburnt soil during daylight hours. Analysis of the soil heat storage data from the flux tower has not yet been conducted and will hopefully provide a more detailed explanation of the mechanisms behind this result.

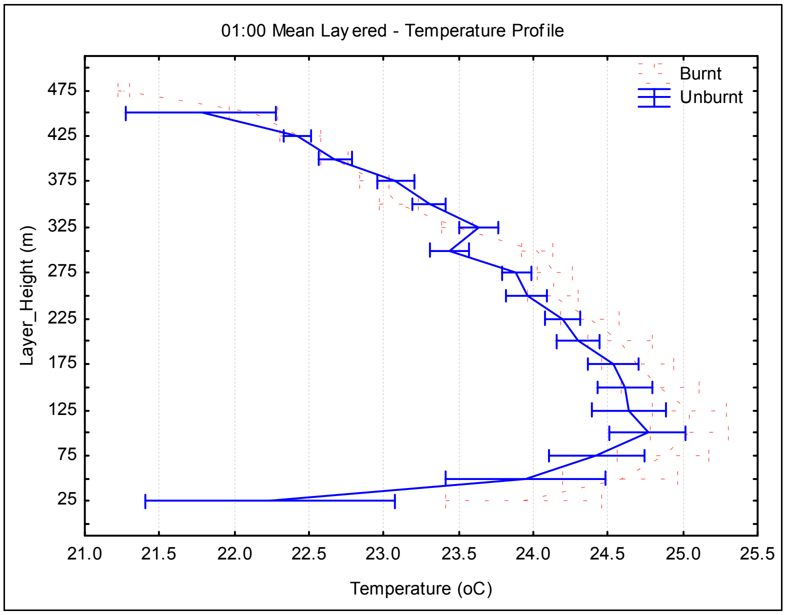

Figure 6: 01:00 mean layered temperature profiles from 13 days of simultaneous soundings from the burnt and unburnt sites (between days 247-276). The burnt site is represented by solid red line and the unburnt site by a dashed blue line.

By 09:00 surface heating from incoming solar radiation is evident and a clear temperature lapse is seen at both sites (Figure 7). Both soundings continue to record similar temperatures throughout the profiles with no statistically significant differences present.

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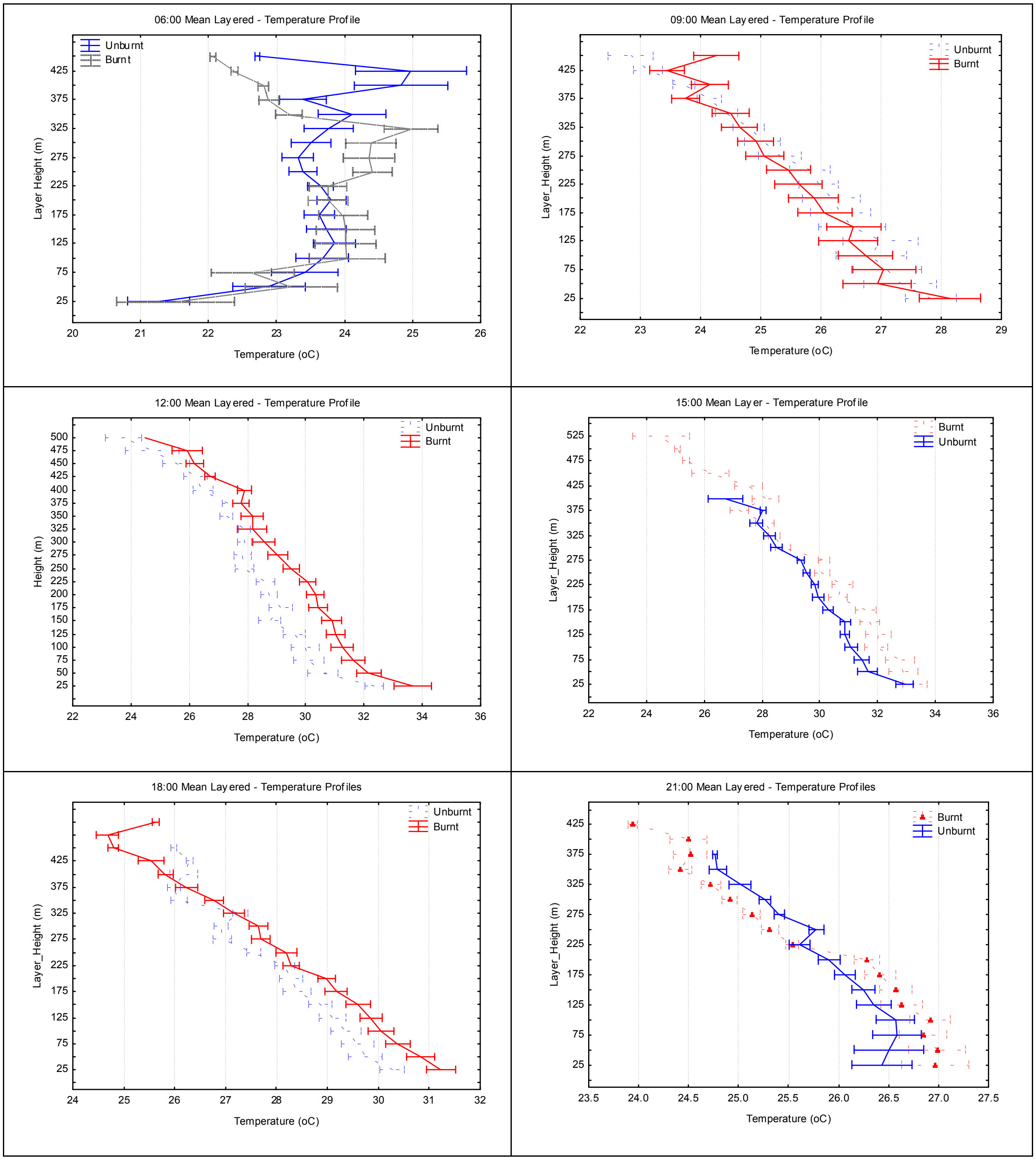

Figure 7: Mean layered temperature profiles from 13 days of simultaneous soundings from the burnt and unburnt sites (between days 247-276). Profiles show mean temperature data for each 25m layer, (i.e. first point at 25m is equal to the mean of all data points from 0 to 25m). The burnt site is represented by solid red line and the unburnt site by a dashed blue line.

Maximum heating differences are seen at 12:00 and 15:00 when the sensible heating of the overlying atmosphere, convection and turbulence over the burnt surface is at a maximum. The burnt site was also found to have slightly higher mean wind speeds throughout the profiles (data not shown) with further analysis of data currently underway.

At 18:00 a temperature lapse is still evident, with the burnt site remaining significantly warmer up to 200 m. At 21:00 surface temperatures have cooled by up to $4^{o}C$ and the burnt site still exhibits a warmer profile up to 200m after which there is a sudden crossover and the unburnt site becomes warmer than the burnt site by similar magnitude (Figure 7). A more in-depth analysis of the data reveal that this was not the result of any single run used to calculate the mean data, rather it was a recurring event. Further analysis of wind direction and humidity data is needed to investigate the drivers behind this phenomenon, but initial results suggest that it may be the product of a displaced air mass producing relative cooling over the site.

6. CONCLUSION

Once burnt, tropical savanna land types showed a significant decrease in albedo and a fundamental change in the partitioning of available energy. Bowen ratios of 2.5 for unburnt savannas indicated that more energy was being partitioned into sensible heat than into latent heating. This is expected during the dry season, as there is low available soil moisture with low canopy LAI. However fire events increase the β three-fold to 6.1, indicating a substantial increase in sensible heat flux to the atmosphere, which combined with convection and mixing, is the driver behind boundary layer heating. For comparison, deserts exhibit β values of ~7.0 (Oke., 1987).

In contrast to previous studies (Beringer *et al*., 2003), the effect of the fire scar in the weeks following the burn was not as significant, which was a direct result of the influence of rainfall. However, taking this into account, the effect of the surface changes on the overlying atmosphere was still clearly evident. At times of maximum heating, air above savanna fire scars are up to $2^{o}C$ warmer than unburnt areas. Due to operating restrictions it was not possible to measure to the top of the boundary layer (estimated from Darwin BOM data to be 1.5 – 3km deep depending on daily conditions) so the depth to which these effects occur cannot be shown. However, increased heating of the boundary layer was evident over the burnt site to the maximum height of 625 m during individual soundings. If no rainfall was present after the fire or the fire intensity was to increase, it could be assumed that heating of the boundary layer may also increase.

Depending on local conditions such as aerodynamic changes to savanna vegetation, the size and intensity of the fire and enhanced sensible heat fluxes over scars, it is possible that these areas could produce localized areas of convergence and divergence and associated mesoscale circulation systems (Knowles, 1993). The possible formation of mesoscale circulations may lead to an increase in convective cloud development and precipitation following a fire event, altering local conditions until pre-fire conditions are restored (Beringer *et al*., 2003). This is highly dependant on the availability of atmospheric water vapour, which is highly seasonal. The intensity of late dry-season fires are often an order of magnitude greater than early or mid dry-season fires (Williams *et al*., 1998) and occur at times when there is greater atmospheric moisture available (pre-monsoonal period of August-October), so it is entirely possible that large scar fire scars could significantly modify regional precipitation patterns (Beringer *et al*., 2003).

With a shift in fire regimes from an early-dry season (April to May) Aboriginal patch burning, to the current regime of more destructive late-dry season fires (Braithwaite, 1991; Williams et al., 1998), large intense landscape scale fire scars are more likely to occur. With the ability of these fire scars to alter the overlying atmosphere as demonstrated by this study, it is possible that they may, once integrated over the total area of Northern Australia, impact on regional climate. Recent studies such as Johnson *et al*., (1999), Williams, *et al*., (2001) and Beringer *et al*., (2003) further emphasise the importance of understanding vegetation-atmosphere interactions under changing fire and weather regimes and also point to possible feedbacks between these changes and regional climate (such as the Australian monsoon). Future work in this study is to apply a mesoscale climate model (MM5 – developed by PSU/NCAR http://box.mmm.ucar.edu/mm5/) to quantify the effect of fire scars on local and regional scale climate. This will improve understanding of how atmospheric processes may be altered under changing fire and climate regimes.

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