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Interaction between Coherent Structures and Surface Temperature and its Effect on Ground Heat Flux in an Unstably Stratified Boundary Layer

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Abstract:

Surface layer plumes, thermals, downdrafts, and roll vortices are the most prominent coherent structures in an unstably stratified boundary layer. They contribute most of the temperature and vertical velocity variance and their time scales increase with height. The effects of these multi scale structures (surface layer plumes scale with surface layer depth, thermals scale with boundary layer height and the resulting roll vortices scale with convective time scale) on the surface temperature and ground heat flux were studied using turbulence measurements throughout the atmospheric boundary layer and the surface temperature measurements from an infra-red camera. Plumes and thermals imprint on the surface temperature as warm structures and downdrafts imprint as cold structures. The air temperature trace shows a ramp like pattern, with small ramps overlaid on a large ramp very close to the surface; on the other hand surface temperature gradually increases and decreases. Turbulent heat flux and ground heat flux show similar patterns, with the former lagging the latter. The maximum values of turbulent heat flux and ground heat flux are 4 and 1.2 times the respective mean values during the ejection event. Surface temperature fluctuations follow a similar power law exponent relationship with stability as suggested by surface layer similarity theory.

Keywords: Atmospheric turbulence, Experimental techniques, Turbulent convection, Turbulent heat and mass transfer

1. Introduction

Coherent structures play an important role for turbulent momentum, heat and mass transport processes in an unstably stratified boundary layer. Laboratory experiments of turbulent free convection [1 – 8] and classical Rayleigh-Bénard convection ([9, 10]; and the references therein) show that in purely thermally driven turbulence most observed coherent structures are warm fluid ascending mushroom-like from the warm surface, cold fluid descending mushroom-like from the cold surface, and resulting large scale circulation. The qualitative nature of these coherent structures can be modified by adding background shear. In the shear-dominated forced convective regime, temperature acts as a passive scalar and the coherent structures become long and streaky with alternating high and low speed fluid [11 – 13]. In a convective atmospheric boundary layer (CBL), the observed coherent structures show different characteristics based on the relative strengths of buoyancy and background shear.

In the logarithmic layer of the CBL, known as surface layer (Figure 1), both shear and buoyancy play dominant roles in turbulent transport. Intermittent warm rising air, known as surface layer plume, is the most common coherent structure [14 – 19]. These plumes are tilted by about 45° due to shear, move with the averaged wind speed over their depth, and have diameters on the order of the surface layer height. They are separated from each other by weaker cold downdrafts. Thus the temperature trace across them shows a sawtooth like pattern [20 – 23], which acts as a genesis of the surface renewal method. According to the surface renewal method, a cold air parcel descends to the ground during the sweep event, as it remains close to the ground it is heated, and when it achieves sufficient buoyancy the warm air parcel ascends during the ejection event.

As the surface layer plumes ascend to the 'outer layer' of the CBL, known as the mixed layer, they merge with each other to create thermals with diameters on the order of CBL depth. These thermals cause intense vertical mixing, resulting in constant wind speed, potential temperature and moisture in the mixed layer. The warm updraft and cold downdrafts together constitute roll vortices in the mixed layer [24 – 30] with time scales on the order of the convective eddy turnover time scale.

These coherent structures of the CBL, i.e. surface layer plumes, thermals, downdraft, roll vortices, imprint themselves onto the surface through modification of heat transport between the surface and the air. For example, [21, 31] measured streaky surface temperature patterns along the wind direction with 2 °C temperature heterogeneity using an airborne thermal infra-red (IR) camera. [19, 22, 32] observed surface temperature fluctuations with an amplitude of 0.5 °C over 2.6 m high maize crops, greater than 2 °C over 1 m high grass, and 2-4 °C over a desert area respectively using an IR temperature sensor. Using an IR camera mounted on a tall tower, spatial heterogeneities in the magnitude of surface temperature fluctuations were also observed by [33, 34] in a grass canopy, [35] in a bare field, [36, 37] in an urban street canyon, [38] in an artificial turf field, and [39] in an urban environment. [40 – 42] observed similar surface temperature coherent patterns in laboratory experiments.

Ballard et al. [33] postulated that high frequency surface temperature fluctuations are caused by turbulent mixing. Katul et al. [32] and Renno et al. [19] hypothesized that surface temperature fluctuations are caused by inactive eddy motion governed by convective mixed layer processes. Christen and Voogt [36, 37] qualitatively attributed the vertical heat transport to coherent structures whose imprints were observed in the surface temperature field moving along the wind direction. Garai and Kleissl [38] studied temporal and spatial evolution of surface temperature patterns in the context of the surface renewal concept. The surface temperature patterns showed large cold structures during sweep events, small patches of warm structures in a cold background during the transition from sweep to ejection, large warm structures during the ejection events and small patches of cold structures in a warm background during the transition from ejection to sweep. Christen et al. [39] reported different surface temperature standard deviations over different surfaces (metallic roofs > lawns > roads > building walls) for an urban measurement site. Direct numerical simulation of solid-fluid coupled turbulent heat transport [43] and land-atmosphere coupled heat transport model [44] revealed that the imprint of fluid temperature fluctuations on the surface depends on the relative thermal properties of the fluid and solid. Hunt et al. [45] observed different forms of coherent structures (plumes, puffs etc.) by varying surface thermal properties in their direct numerical simulation of solid-fluid coupled turbulent heat transport process.

The main objective of the present experiment is to study the influence of different coherent structures with widely varying scales in the CBL on the surface temperature and ground heat flux at different levels of thermal instability. A unique dataset was collected that spans from thermal imagery of the surface to wind and temperature measurements through the CBL. Spectral density and probability density functions were employed to study the evolution of air temperature fluctuations with height and compare them against surface temperature fluctuations. The solid-fluid coupled heat transport mechanism was then studied by identifying coherent structures at different heights. In Sections 2, 3, and 4 we will describe the experimental technique, results, and conclusions respectively.

2. Experimental technique

The experiment was conducted in collaboration with Boundary Layer Late Afternoon and Sunset Turbulence [46] field campaign at Centre de Recherches Atmosphériques, Lannemezan, France from 14 June to 8 July, 2011 (Figure 1). Surface temperature (T_s) at 1 Hz was recorded using a FLIR A320 Thermal IR camera with an accuracy of 0.08 K. It was mounted at 59 m above ground level a.g.l. on a 60 m tall tower (43°07'25.15" N, 0°21'45.53" E) looking towards 55° N with an inclination of 2° from 16 to 29 June, 2011 (Case L for "large" field of view of the IR camera) and looking towards 115° N with an inclination of 45° from 30 June to 8 July, 2011 (Case S for "small" field of view of the IR camera). The main motivation for using two different camera field of views was to be able to vary the largest and smallest observable surface temperature scales. Note that – consistent with nomenclature in the atmospheric sciences – y is the cross-stream and z is the wall-normal direction. Details of the IR camera field of view can be found at Appendix A.

The air turbulence of different regions (near surface, $z < 0.8$ m; lower surface layer, 0.8 m $< z < 10$ m; upper surface layer, 10 m $< z < 1/10z_i$; and mixed layer $1/10z_i < z < z_i$, where z_i is the inversion height) was probed at different heights inside the camera field of views (Table 1 and Figure 1) by different sensors. The mean wind speed, potential temperature and humidity vertical profile was measured by radiosondes ("Sounding" in Figure 1) and net radiation was measured by different radiation sensors ("Radiation Tower" in Figure 1) during the experiment. All measurement platforms were GPS synchronized to Coordinated Universal Time (UTC) which lags local standard time by 2 hours.

Finally about one month of quality controlled data (Appendix B) was characterized using 2 m sonic data for Case L and 2.4 m sonic data for Case S by evaluating the friction velocity (Equation 1a), the convective velocity (Equation 1b), the surface layer temperature scale (Equation 1c), the mixed layer temperature scale (Equation 1d), the Obukhov length (Equation 1e), and the flux Richardson number (Equation 1f):

$$u_* = (\langle u'w' \rangle^2 + \langle v'w' \rangle^2)^{1/4}, \tag{1a}$$

$$w_* = \left(\frac{g z_i}{\langle T_a \rangle} \frac{H}{\rho_a c_{p,a}} \right)^{1/3}, \tag{1b}$$

$$T_*^{SL} = \frac{\frac{H}{\rho_a c_{p,a}}}{u_*}, \tag{1c}$$

$$T_*^{ML} = \frac{\frac{H}{\rho_a c_{p,a}}}{w_*}, \tag{1d}$$

$$L = -\frac{\langle T_a \rangle u_*^3}{\kappa g \frac{H}{\rho_a c_{p,a}}}, \tag{1e}$$

$$Ri_f = \frac{\frac{g}{\langle T_a \rangle} \frac{H}{\rho_a c_{p,a}}}{u_*^2 \frac{dM}{dz}}, \tag{1f}$$

where κ, g and $\frac{H}{\rho_a C_{p,a}}$ are von Kármán constant, gravitational constant and turbulent sensible heat flux (estimated using $\frac{H}{\rho_a C_{p,a}} \approx \frac{\langle wT_a' \rangle}{(1+0.06/B)}$, where ρ_a, $C_{p,a}$ and B are the dry air density, dry air specific heat and the Bowen ratio , defined as the ratio between sensible and latent surface heat fluxes). B is used to correct sonic temperature fluctuations for humidity fluctuations and estimated using a CSAT and LICOR 7500A CO_2/H_2O analyzer mounted at 29.3 m. The vertical gradient of horizontal wind speed $\mathrm{d}M/\mathrm{d}z$ was estimated using Businger-Dyer similarity relationships [47, 48].

A unique aspect of our study is that the ground temperature and heat flux can be forced independently with the measured surface temperature. The ground heat flux, G is estimated from the transient 3-D heat conduction equation

$$\frac{\partial T_g}{\partial t} = \alpha_g \left(\frac{\partial^2 T_g}{\partial x^2} + \frac{\partial^2 T_g}{\partial y^2} + \frac{\partial^2 T_g}{\partial z^2} \right), \tag{2a}$$

where α_g and T_g are thermal diffusivity and temperature of the ground, respectively. The boundary conditions are the IR camera measured surface temperature at the top (z = 0 m) and adiabatic conditions ($\frac{\partial T_g}{\partial z} = 0$) at the bottom boundary (z = -5.5 m). The conduction equation was discretized horizontally using a spectral method with periodic boundary conditions; vertically using a second order finite difference scheme; and then time was advanced by the Euler implicit scheme. The numerical solution of Equation 2a was successfully validated against the analytical solutions of constant and sinusoidally varying surface temperature (not shown). The ground temperature in the domain was initialized by $T_g(x, y, z, t = 0) = T_\infty + \frac{\langle G \rangle}{k_g} \left\{ 2 \left(\frac{\alpha_g \tau}{\pi} \right)^{1/2} \exp\left(-\frac{z^2}{4\alpha_g \tau} \right) + \frac{z}{2} \mathrm{erfc}\left(-\frac{z}{2\sqrt{\alpha_g \tau}} \right) \right\}$, where $\langle G \rangle = \langle R_{net} - \left(1 + \frac{1}{B}\right) H \rangle$ is the mean surface heat flux obtained from the surface energy balance, $\tau = \left[\frac{k_g(\langle T_s \rangle - T_\infty)}{2\langle G \rangle} \right]^2 \frac{\pi}{\alpha_g}$ is a dummy time [49], T_∞ (= 288 K) is the soil temperature at $z \to -\infty$ (corresponding to the mean annual air temperature) and erfc is the complementary error function. To minimize the effect of unrealistic initial conditions, we neglected the first 100 time steps for simulation spin-up. Since the ground temperature gradient peaks near the surface, the vertical grid resolution was set to 1.5 mm there; below z = -0.05 m the vertical grid was stretched uniformly to 0.1 m resolution. The heat flux at the surface (G) was then computed from T_g as:

$$G = \left[\frac{\Delta z}{2\Delta t} \int_{\Delta t} \rho_g C_{p_g} \frac{\partial T_g}{\partial t} dt \right] - \left[\frac{\Delta z}{2\Delta x} \int_{\Delta x} k_g \frac{\partial^2 T_g}{\partial x^2} dx + \frac{\Delta z}{2\Delta y} \int_{\Delta y} k_g \frac{\partial^2 T_g}{\partial y^2} dy \right] + \left[k_g \frac{T_s - T_{g,-\Delta z}}{\Delta z} \right], \tag{2b}$$

where ρ_g, C_{pg}, k_g, Δx, Δy, Δz are density, specific heat, and thermal conductivity of the ground and grid size in horizontal and vertical directions respectively [34].

3. Results and discussion:

The clear days (19, 20, 24, 25, 26, 27 and 30 June; and 1, 2, and 5 July) were selected for further analysis. Amongst these days, the 30 min. periods which satisfy the stationarity conditions (standard deviation of six 5 min mean wind speed less than 15% of the mean wind speed and standard deviation of six 5 min wind direction less than 20_0) were considered for detailed analysis. This resulted in 32 stationary periods (Table 2) with L ranging from -1.12 m to -37.23 m. We have chosen $L = -6.68$ m (Period 8.L) and -14.33 m (Period 22.L) as representative periods for more stable and less unstable boundary layer to illustrate our findings, as high quality data from most sensors were available. Since mixed layer (LIDAR) data ($0.1 \leq z/z_i \leq 1$) for $L = -6.68$ m were not available a period with $L = -6.22$ m (Period 7.S) was chosen instead for section 4e-iii, which had surface temperature measurement with upper surface layer turbulence measurements. All other stationary periods reveal qualitatively similar findings.

a) Spatial evolution of temperatures

At a given time the surface temperature shows large warm and cold structures aligned with the mean wind (Figure 2). Animations of these structures reveal that they grow in size, combine with each other and continue to move with the wind (see the supplemental material). Previous studies [19, 21, 31 – 39, and 44] attributed these surface temperature structures to turbulence in the overlying flow. To test this hypothesis, in Figure 2, time series of air temperature over different heights were mapped on the surface temperature along the mean wind direction using the advection speed of the surface temperature structures and assuming Taylor's frozen turbulence hypothesis. Autocorrelation of the surface and air temperature reveal that they have similar characteristic time scales. By calculating cross-correlations between the air and the surface temperature, previous studies by [32] and [38] showed that the surface temperature structures are advected by higher level winds. The cross-correlation between the air temperature of 8 m sonic and the surface temperature showed correlations up to 0.3 – 0.4 for the moderately unstable regions considered (Table 2). The upwind surface temperature precedes the air temperature at the measurement location, and vice-versa. The advection speeds were shown to be similar to the 8 m a.g.l. wind speed by cross-correlating the air temperature of different heights with the surface temperature along the mean wind direction [34]. Figure 2 shows that warm (cold) air is generally associated with positive (negative) vertical velocity due to its buoyancy, as expected in a CBL. Air temperature is correlated with the surface temperature. Small discrepancies in the air and surface temperature structures can be attributed to variations in the wind direction violating Taylor's hypothesis. Also the air and surface temperature structures are of the same order in space and time. The mean size of the surface temperature structures increases with the decrease in the instability of CBL. The measured standard deviation of surface temperature revealed that the surface temperature fluctuations are representative of a grass surface (discussed further in section 4c).

b) Temperature spectra

The statistical behavior of the air and surface temperature fluctuations was then studied using spectral analysis. To reduce the noise of the spectral density, ensemble averages of three 10 min intervals in a 30 min stationary period were computed. In addition, a linear fit was applied to spectral densities for smaller frequencies ($f < 0.005$ Hz); spectral densities at higher frequencies were filtered with logarithmically spaced windows (Figure 3).

The air temperature spectral density closely follows the classical $-5/3$ Kolmogorov law in the inertial range (Figure 3-c) except near the surface ($z < 0.8$ m). Near the surface, small scale fluctuations of the air temperature become more energetic, causing it to decay slower than the $-5/3$ Kolmogorov law. The strength of higher frequency air temperature fluctuations decreases with height, while that of low frequency fluctuations remains of the same order. Near the surface (Figure 3-aii and 3-bii, $z < 0.8$ m for our data) the temperature spectral density does not change with height.

Surface temperature fluctuations, on the other hand, exhibit less energetic high frequency components. Hence the surface temperature spectral density decays faster compared to the classical $-5/3$ Kolmogorov law (Figure 3c). This can be attributed to the fact that the surface temperature fluctuations are forced by the air temperature fluctuations and the high frequency surface temperature fluctuations are damped as the surface has larger thermal inertia compared to the air.

c) Scaling of r.m.s. temperature

The normalized air temperature standard deviation (the integral of the temperature spectral densities) also decreases with height (Figure 4) following the surface layer similarity theory: ${\sigma_{Ta}}/{T_*^{SL}} = 0.95\left(-{z}/{L}\right)^{-1/3}$ [15]. Very close to the surface (0.09 m < z < 0.8 m) where the spectral density does not change with height, the normalized air temperature standard deviation deviates from similarity theory. Previous studies also reported the deviation of ${\sigma_{Ta}}/{T_*^{SL}}$ from similarity theory for small -z/L. In a less unstable (larger $-L$, such that $-z/L$ smaller) CBL, [50 – 53] reported that ${\sigma_{Ta}}/{T_*^{SL}}$ asymptotes to about 3, whereas [54] reported the asymptote value to be 6.56. Our measurements close to the ground (smaller z), show that the asymptote value of ${\sigma_{Ta}}/{T_*^{SL}}$ is larger than 3 for smaller $-z/L$. Thus, the discrepancy of ${\sigma_{Ta}}/{T_*^{SL}}$ very close to the surface, while consistent with the spectra analysis in section 3b, indicates a failure of Monin-Obukhov similarity theory.

Since the spectra for surface temperature decay fast with frequency compared to very near surface air temperature, ${\sigma_{Ts}}/{T_*^{SL}}$ is smaller (Figure 4), but it follows a power law exponent

($\sigma_{Ts}/T_*^{SL} = -0.36(-\zeta)^{-0.39}$, where ζ = 2.23 m/L for Case L and 2.4 m/L for Case S) comparable to the one predicted by similarity theory. The measured σ_{Ts} for a solid-fluid coupled heat transport depends on the thermal activity ratio, *TAR* (= $\frac{k_f}{k_s}\sqrt{\frac{\alpha_s}{\alpha_f}}$, where k and α are thermal conductivity and thermal diffusivity of the fluid, subscript "*f*", and the solid, subscript "*s*") [43, 44]. Assuming thermal properties of air (k_f = 0.025 W m^{-1} K^{-1}, α_f = 20 mm^2 s^{-1}), the homogeneous clay soil with 40 % volumetric water content (k_s = 0.8 W m^{-1} K^{-1}, α_s = 0.4 mm^2 s^{-1}) and the grass with 1000 leaves m^{-2} and a weight of 10^{-3} kg per leaf (k_s = 0.38 W m^{-1} K^{-1}, α_s = 19.62 mm^2 s^{-1}) gives *TAR* = 0.0044 for the soil-air and = 0.07 for the grass-air heat transport mechanisms. Although DNS results by Tiselj et al. [43] and Hunt et al. [45] should be compared with field experiment data cautiously due to the disparity in the Reynolds number, the strength of instability, and the moisture transport, the estimated values of σ_{Ts} by [43] and [45] revealed that the present σ_{Ts} is more consistent with the heat transport from grass to air [34].

d) Temperature probability density function

To investigate the cause of the behaviour of temperature spectral density with height in the surface layer, we move our attention towards the evolution of the temperature probability density function (pdf) and vertical velocity with height (Figure 5). The temperature pdfs above $z \approx 1$ m show distinct characteristics: i) the high probability density region is concentrated towards negative temperature, ii) a short tail for negative temperature, and iii) a long tail for positive temperature fluctuations (Figure 5-i). The most probable value (mode) increases with measurement height. The *magnitude* of vertical velocity corresponding to the negative temperature fluctuations is smaller than that corresponding to the positive temperature fluctuations. As cold fluid descends, the temperature difference to the warm superadiabatic background increases, but the close proximity to the surface causes the magnitude of its vertical velocity to decrease. This phenomenon results in the slow downdraft of cold fluid parcels. On the other hand, warm fluid ascends and accelerates through the boundary layer due to buoyancy. Thus the warm fluid near the surface causes larger velocities and more intermittent updraft events. Similar characteristics of air temperature probability density functions were observed by [55].

Very close to the surface ($z < 0.8$ m), the characteristics of the temperature pdf change (Figure 5-ii). Since more of the total variance is due to small scale events (Figure 4), the temperature fluctuations become almost normally distributed. Likewise at the surface the temperature pdf is normally distributed, but the spread of the surface temperature distribution is smaller compared to the very near-surface air temperature distribution (see Section 3b for possible explanations).

Comparing Figure 5a with 5b, the spread of the temperature fluctuations for different stationary periods also depends on stability. As the boundary layer becomes less unstable, the spread decreases, irrespective of the height considered. This is a result of the decrease in relative strength of buoyancy compared to shear, which reduces the occurrence of large intermittent buoyant events.

e) Conditional averaging to identify interaction of sweeps and ejections with surface temperature

To explain the characteristics of temperature spectral density and pdf, conditional averaging was employed to study the dominant coherent structures. The ejection events in the surface layer were identified using turbulence signals at a height h by $w'T_a{}'_h > 0.5\langle w'T_a{}'\rangle_h$ with positive *w'* and the sweep events are identified by $w'T_a{}'_h > 0.25\langle w'T_a{}'\rangle_h$ with negative *w'*. The chosen cut-off values ensure positive identification of large events, yet select enough events to achieve statistical convergence. The higher cut-off value for ejection events compared to sweep events is motivated by the increased strength of ejection events compared to sweep events [17, 18]. Since temperature data was not available for $z > 60$ m, coherent structures were identified through the LIDAR vertical velocity signal w, which results in the detection of similar events as below 60 m since vertical velocity and temperature are highly correlated in an unstably stratified boundary layer. From the LIDAR data, ejection and sweep events are identified by $w'_h > 0.4\sqrt{\langle w^2\rangle_h}$ and $w'_h < -0.4\sqrt{\langle w^2\rangle_h}$ respectively. Additional requirements for an event were: (i) a minimum duration, (ii) a minimum separation between two consecutive events (criteria varied as a function of height h) as described below, and (iii) passing a visual inspection. Since the duration of each ejection (sweep) event is different, time was normalized by the individual ejection (sweep) time scale such that $t = 0$ and 1 indicates the start and end of the ejection (sweep) event respectively. Though the quantitative value of the statistics derived from the ejection and the sweep events will depend on the definitions (i.e. the thresholds), the qualitative nature of the statistics is independent of the definitions.

i) Lower surface layer and near-surface:

The ejection and sweep events in the lower surface layer (0.8 m < z < 10 m) and near-surface (z < 0.8 m) were identified using the turbulence signals at 8 m a.g.l. with a minimum time scale of 3 s and minimum separation between events of 5 s. These criteria result in 20 to 30 ejection events (30 to 40 sweep events) per stationary period with time scales ranging from 3 s to 45 s (3 s to 60 s). The separation between the ejection and sweep events is about 5 – 15 s, whereas that between the sweep and ejection events is about 15 – 45 s. The ejection and sweep events together represent 60% of the 30 min periods with most of the air temperature (80%) and vertical velocity (70%) variance, and are solely responsible for the sensible heat flux (about 100%) for all the stationary periods (Table 3).

During the initiation of ejection events, as the air warms, it gains buoyancy. With sufficient buoyancy the warm air parcel ascends from the surface to constitute surface layer plumes and as they rise further, they combine with each other to create larger plumes. When the plumes ascend through the boundary layer, convergence near the surface causes cold air to descend. Hence, the air temperature trace through plumes in the lower surface layer shows a ramp-like pattern; air temperature slowly increases during the initial part of the ejection, attains a maximum at the end of ejection event, and drops quickly during the transition from ejection to sweep event (Figure 6). Small scale ramps are overlaid on the large ramp and the number of small ramps was found to decrease with height (visual examination on individual ejection events revealed about 4 to 5 small ramps at 0.5 m a.g.l. and 2 to 3 small ramps at 8 m a.g.l. on a large ramp) as small scale fluctuations decrease with height (Figure 3).

The interaction between surface and air during the event also offers unique insights. As the near-surface air warms up during the initial phase of the ejection event ($t < 0.5$), the heat flux from the surface to air decreases. Thus the surface energy budget causes warming of the surface and an increase in ground heat flux. When the warm air ascends from the surface ($0.5 < t < 1$), the majority of the heat exchange between the surface and air occurs, resulting in cooling of the surface. The surface temperature is only influenced by the large scale plume (Figure 6-ii) and not by smaller plumes apparent in the air temperature. As the probability density functions and spectra from the two different camera fields of views (and associated difference in horizontal resolution) of the IR camera are similar, we conclude that the lack of small scale plume signatures is not an artifact of insufficient spatial resolution. It might be due to the larger thermal inertia of the surface or insufficient temporal resolution of the measurements, as mentioned earlier.

In a sweep event (Figure 7) cold air approaches and cools the surface. As the cold air parcel descends, its vertical velocity decreases due to the proximity of the surface. At ($t > 0.5$) the heat transport from the surface to air starts to decrease, resulting in an increase in surface temperature and ground heat flux. Also note that the 8 m air temperature during sweep events ($0 < t < 1$ in Figure 7) remains almost constant compared to during ejection events ($0 < t < 1$ in Figure 6). During the transition from sweep to ejection ($t > 1$), the air temperature slowly increases, in contrast with the sharp transition from ejection to sweep.

Consequently, the combination of sweeps and ejections causes the air temperature trace in the lower surface layer to be sawtooth-like: almost constant during the sweep, gradual increase until the end of the ejection, and thereafter a sharp drop. On the other hand the surface temperature increases and decreases smoothly. With increase in stability, background shear increases and thus the tilt of the plumes is also expected to increase especially near the surface as confirmed in the figures.

ii) Upper surface layer

The coherent structures in the upper atmospheric surface layer (10 m < z < 0.1z_i) were detected using the turbulence measurements at h = 45 m. As larger scale turbulent motions become more energetic with height (Figure 3), we used 15 s as minimum timescale of an event and 5 s as minimum separation between events. These criteria result in 8 to 10 ejection events (about 12 sweep events) per stationary period with time scales ranging from 15 s to 60 s (15 s to 90 s). The separation between the ejection and sweep events is about 5 – 10 s, whereas that between the sweep and ejection events is about 10 – 20 s. The ejection and sweep events together represent about 45% of the 30 min periods with most of the air temperature (about 50%) and vertical velocity (about 60%) variance, and are solely responsible for turbulent heat flux (about 100%) (Table 3).

For the upper surface layer events, the plumes also imprint on the surface as warm structures, whereas the cold sweep events imprint on the surface as cold structures (Figure 8). As the IR camera field of view was smaller during Case S, the pixel size is smaller compared to that during Case L, which may be the cause of more small scale fluctuations in the conditionally averaged surface temperature. However, the smaller number of events may also be a contributing factor.

In the upper surface layer the magnitude of temperature fluctuations decreases compared to the lower surface layer. Compared to the lower surface layer, the plume characteristics in the upper surface layer are that i) the increase in air temperature across the plume is smaller and ii) the drop in air temperature after the ejection event is sharper. The sharper drop of temperature after the ejection event can be attributed to the increase in vertical velocity with height, causing stronger convergence of the flow at the ejection-sweep transition.

As the small scale plumes ascend from the lower surface layer to the upper surface layer, they merge with each other to create large plumes, which results in almost constant temperature inside the plumes in the upper surface layer, in contrast with the lower surface layer. Thus the characteristic ramp-like pattern of the air temperature trace also changes with height: constant during the sweep, gradual increase during the transition from sweep to ejection, *constant during the ejection*, and *rapid decrease during the transition from ejection to sweep*. The tilt of the plumes is reduced due to the decrease in background shear with height.

iii) Mixed layer

To study the mixed layer (0.1 < z/z_i < 1) turbulent structures, h = 200 m (h/z_i = 0.4 for the stationary period considered) with 60 s as minimum time scale and minimum separation between two consecutive events was used. These criteria result in about 4 ejection and sweep events (accounting for 45% of vertical velocity variance) in the 30 min stationary periods (Table 3) and the separation between them is about 5 – 10 s. The average time scale (of about 3 – 5 min) for ejection or updrafts and sweep or downdrafts is consistent with the eddy turn-over time scale (z_i/w_*) for the CBL.

Thermals in the mixed layer are formed from the merging of several surface layer plumes and surface layer sweep events are caused by cold downdraft from the mixed layer. Thus the surface temperature shows warm structures beneath the thermals and cold structures beneath the downdrafts (Figure 9). Since the boundary layer is well mixed in this region, the background shear is negligible. Thus the thermals and downdraft in the mixed layer show almost no tilt. The magnitude of the vertical velocity decreases with height (z/z_i > 0.5) due to stably stratified capping inversion. The vertical velocity standard deviation peaks at $z/z_i \approx 0.3 - 0.4$, consistent with other experimental observations and numerical simulations of the CBL [8, 25].

f) Heat fluxes at the earth's surface

The effect of the plumes and sweeps in the surface layer; and thermals and downdrafts in the mixed layer on the surface energy budget is now investigated

$$R_{net} - G = H + LE + S, \tag{3a}$$

where R_{net}, G, H, LE and S are the net radiation, ground heat flux, sensible heat flux, latent heat flux and heat storage by the canopy, respectively. Since our experimental site is covered only by grass and our stationary periods occur well outside of sunrise and sunset, the canopy storage term is negligible [56]. Also, since high frequency humidity measurements were not available near the surface, we have estimated the latent heat flux from the Bowen ratio, B, at 29.3 m a.g.l. Thus Equation 3a becomes

$$R_{net} - G \approx H\left(1 + \frac{1}{B}\right). \tag{3b}$$

Assuming R_{net} to be constant within the 30 min stationary (cloud-free) periods, the coherent structure induced H variation should then be balanced by G.

Though the measured T_s is of the most representative of grass, we solved the 3D transient heat conduction equation (Equations 2) using the thermal properties of the homogeneous clay soil with 40% volumetric water content. The resulting normalized ground heat flux ($G/\langle G\rangle$) will be independent of surface thermal property as the heat conduction equation is linear.

During ejection and sweep events, computed G and measured $w'T_a'$ at 8 m a.g.l. show similar behaviour for different stationary periods (Figure 10). The majority of heat transport from the surface to air occurs during the end of the ejection event (reference also Figure 6). Thus G attains a minimum during this time following Eq. 3b. During the initial phase of the ejection, $w'T_a'$ increases and the ground heat flux, G, attains a maximum. During the sweep event cold air descends to the ground, heat transport from surface to air decreases compared to the ejection period (since the ground is cold, cf Figure 7), and G is also depressed. As these cold air parcels near the surface warm up, even less heat will be transferred from the surface to the air, and G starts to increase. Thus the ground heat flux succeeds the turbulent heat flux. For our data, during the ejection event turbulent coherent structures cause the turbulent heat flux to be about 4 times the average and the ground heat flux to be about 1.2 times the average.

Since high frequency humidity data were not available, we could not demonstrate the behavior of latent heat transport and how it influences the ground heat flux through a decoupling from the sensible heat flux that violates the assumption in Equation 3b. Also, for this comparison we have neglected the influence of mechanical heat transport ($\frac{d}{dx}\int_0^h uTdz$) by horizontal wind (since we are comparing G at $z \approx 0$ m with $w'T_a'$ at $z = 8.22$ m). Since during the sweep event the fluid velocity is high with low temperature and during the ejection event the fluid velocity is low with high temperature, the missing dynamical estimates of latent heat and mechanical heat transport can account for the imperfect balance between G and H which has been discussed in the context of Equation 3b.

4. Conclusions

In this work we studied turbulent coherent structures and their influence on the surface temperature and ground heat flux in a CBL experimentally for a wide range of stabilities and found that the larger scales of turbulent heat transport dominate the surface temperature variations. Surface layer turbulence is dominated by plumes/ejections and sweep events. During sweep events, cold air descends, while during ejection events plumes of warm air ascend from the surface layer through the boundary layer due to buoyancy. Near the surface small scale plumes are overlaid on a large scale plume and these small scale plumes merge with each other to create a large plume in the upper surface layer. Thus the temperature trace across the ejection and sweep event in the middle part of the surface layer is constant during the sweep, slowly increases during the transition from sweep to ejection, attains a maximum during the ejection and then drops quickly during the transition from ejection to sweep (ramp like pattern). In the upper surface layer the trace during the sweep-ejection-cycle is similar with the exception that temperature is constant during the ejection. The sweep-ejection-cycle can also be explained using surface renewal analysis [23]. Thus the temperature probability density function shows an exponentially decaying short negative tail with a long positive tail except near the surface. Near the surface a greater abundance of small scale plumes and sweeps makes the temperature pdf close to Gaussian. The spectral density in small scale or high frequency fluctuations decays with height, whereas the spectral density in low frequency fluctuations remains similar with height.

Sweep and ejection events account for most of the temperature and vertical velocity variance and turbulent heat flux, with the majority of the contribution from ejection events. The durations of sweep and ejection events are generally similar except in the lower surface layer (time scales for sweep events are larger near the surface). The durations increase with height and the combination of a sweep and an ejection is close to the convective eddy turn-over time in the mixed layer.

The unique aspect of our study was the observation that these coherent structures – from the lower and upper surface layer and the mixed layer – imprint on the ground heat flux and surface temperature. The ground heat flux precedes the turbulent heat flux and shows a similar pattern during sweeps and ejections, but the surface temperature increases and decreases more gradually, which is distinct from the ramp pattern in air temperature. Similar patterns of temperature of air and surface were also observed in direct numerical simulations (at much lower Reynolds number) by Hunt et al. [45]. We also found that small scale plumes do not imprint on the surface, which might be due to the larger thermal inertia of the ground.

Near-surface air temperature standard deviations deviate from the surface layer similarity theory [15]. Previous studies by [50 – 54] reported that the normalized air temperature fluctuation asymptotes to about $3 - 6$ for small stability (parameterized as z/L). Although the measured standard deviation from the near-surface thermocouple data may suffer from missing high frequency components (the lowest thermocouple is at the height of the roughness elements), the asymptotic value is greater than 3. Surface temperature fluctuations show a similar power law exponent with z/L as in surface layer similarity theory.

Present state-of-the-art large eddy simulations use constant heat flux or constant temperature at the surface. Atmospheric and laboratory scale observations demonstrate that neither choice of the boundary conditions is realistic. Direct numerical simulations by [43, 45] reveal that the near surface turbulence characteristics are functions of surface thermal properties. The present study demonstrates through measurements that both the surface temperature and ground heat flux show evidence of turbulent coherent structures. This proves the necessity of improved wall functions for modeling turbulent heat transport.

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Appendix A: IR camera field of view

During the BLLAST campaign, the surface temperatures for Case L and S were measured using an IR camera. The camera measured longwave radiation (8 – 14 μm wavelength) from the surface in 240 x 320 pixels was then converted to the surface temperature assuming an emissivity of 0.95 [57]. For Case L the camera overlooked a homogeneous 90 mm high grass field with a solar reflectance (albedo) of 0.19 (from measurements) and for the Case S the camera overlooked a less homogeneous field with bare soil, grass, small bushes and small puddles with an average albedo of 0.19. To transform the camera images into a regular Cartesian coordinate system, interpolation and coordinate system transform were performed. This resulted in a camera field of view of 450 m x 207 m with a uniform resolution of 4.5 m x 0.65 m for Case L and 92 m x 59 m with a uniform resolution of 0.38 m x 0.18 m for Case S. 1 hr daytime average of the surface temperature from the IR camera shows road, buildings and bare soil to be warmer and a small pond to be cooler than the grass regions in both Case L and Case S (Figure 1). Thus to limit the effect of surface heterogeneity we ignored the y > 275 m region for Case L during the analysis.

Appendix B. Data processing

Collected surface temperature and air turbulence data was the processed to ensure the quality of data. A coordinate system rotation was conducted to ensure that vertical velocity fluctuations were perpendicular to the mean flow by enforcing $|\langle w\rangle/M| < 1\%$ (angeled brackets denote temporal averaging and M is the mean horizontal wind speed) following [58] and to orient the sonic winds to the IR-camera coordinate systems. The turbulent time series from FWTCs and sonics were detrended linearly using 5 min and 10 min periods for mounting height less than and greater than 10 m, respectively. Ogive tests [59] showed that the above mentioned periods were sufficient to capture > 90 % of the scales responsible for eddy covariance fluxes. For surface temperature, each pixel of the IR images was linearly detrended with the periods corresponding to the turbulence measurement height. For the comparison to LIDAR data, the IR camera data for each pixel were detrended using a 30 min period. Resulting detrended variables are denoted by primes in the subsequent sections.

The quality of the LIDAR data was verified by recovering the classical -5/3 power law spectra of vertical velocity and by comparing the vertical velocity variance with the mixed layer similarity theory [60]. Only LIDAR data with high carrier to noise ratio (> -15 dB) were considered for detailed analysis, eliminating measurements above 400 m.

Also to compare 20 Hz or 10 Hz frequency turbulence time series with 1 Hz surface temperature, we applied a box filter of size 1 s centered at the surface temperature time stamp to the turbulence time series and to compare 0.2 Hz LIDAR data with 1 Hz surface temperature, we applied a box filter of size 5 s centered at the LIDAR time stamp to the surface temperature. The inversion height, z_i, was estimated visually by locating increases in potential temperature of greater than 1 K per 100 m.

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Table 1. List of instruments deployed during the BLLAST field campaign. Positions of each instrument with respect to IR image coordinates (for Case L and S) were also reported in addition to the GPS coordinates.

Case	Sensor name	Height	Acronym	Position		Frequency	Purpose
				GPS	Image	(Hz)	
L	Finewire thermocouples	0.09 m 0.13 m 0.19 m 0.57 m 1.12 m	FWTC	43°07’39.2” N 0°21’37.3” E	x = 0.4 m, y = 185 m	20	Near-surface turbulent air temperature.
	Campbell Sonic Anemometer-Thermometers	2.23 m 3.23 m 5.27 m 8.22 m	2 m sonic 3 m sonic 5 m sonic 8 m sonic	43°07’39.2” N 0°21’37.3” E	x = 0.4 m, y = 185 m	20	Lower surface-layer turbulent velocity and air temperature.
	Windcube 200 LIDAR	100 m, 150 m, …, 400 m	LIDAR	43°07’32.16” N 0°21’52.2” E	x = 27 m, y = −55 m	0.2	Vertical wind speed in the mixed layer.
S	uSonic-3 Scientific	2.4 m	2.4 m sonic	43°07’26.77” N 0°21’46.96” E	x = −5 m, y = 15 m	20	Lower surface-layer turbulent velocity and air temperature.
	Campbell	29.3 m	30 m sonic	43°07’25.15” N	x = −5 m,	10	Upper surface-

Sonic Anemometer-Thermometers	61.4 m	60 m sonic	0°21’45.53” E	$y = -25$ m	layer turbulent velocity and air temperature.
Gill master pro 3D sonic anemometer	45.8 m	45 m sonic			

Table 2. Characteristics for the stationary periods chosen for detailed analysis ordered by stability conditions. The last character in the naming of different stationary periods denotes the IR camera field-of-view (Case L or S).

Period	Time (UTC)	L (m)	Ri_f (-)	$\boldsymbol{u_*}$ (m s^{-1})	$\boldsymbol{w_*}$ (m s^{-1})	$\frac{\boldsymbol{H}}{\boldsymbol{\rho_a C_{p,a}}}$ (K m s^{-1})	z_i (km)
1.S	1230-1300, 2 July	−1.12	−5.11	0.12	1.56	0.116	1.0
2.S	0625-0655, 1 July	−1.77	−2.54	0.10	1.04	0.033	1.2
3.S	0925-0955, 5 July	−5.21	−0.77	0.19	1.50	0.102	0.5
4.L	0930-1000, 27 June	−5.49	−0.66	0.15	0.95	0.045	0.6
5.S	1125-1155, 5 July	−5.71	−0.65	0.21	1.58	0.119	0.7
6.S	0900-0930, 5 July	−6.16	−0.63	0.19	1.42	0.086	0.5
7.S	0800-0830, 5 July	−6.22	−0.64	0.18	1.30	0.066	0.5
8.L	0830-0900, 26 June	−6.68	−0.52	0.15	0.71	0.028	0.4
9.S	0825-0855, 5 July	−7.19	−0.52	0.19	1.34	0.072	0.5
10.L	1100-1130, 20 June	−7.27	−0.47	0.22	1.38	0.113	0.7
11.L	1100-1130,27 June	−8.45	−0.39	0.19	1.15	0.058	0.8
12.L	1030-1100, 27 June	−8.45	−0.39	0.18	1.06	0.053	0.7
13.L	1530-1600, 20 June	−8.84	−0.37	0.19	1.31	0.062	1.1
14.L	0935-1005, 26 June	−9.40	−0.35	0.17	0.82	0.043	0.4
15.L	0825-0855, 27 June	−10.22	−0.31	0.15	0.76	0.027	0.5
16.L	1200-1230, 25 June	−11.74	−0.27	0.26	1.23	0.112	0.5
17.S	1000-1030, 1 July	−11.98	−0.28	0.25	1.49	0.099	1.2
18.S	1600-1630, 5 July	−12.48	−0.27	0.18	1.05	0.035	0.4
19.L	1030-1100, 25 June	−12.49	−0.25	0.27	1.23	0.112	0.5
20.S	1500-1530, 1 July	−13.51	−0.25	0.25	1.39	0.080	1.2
21.S	0700-0730, 5 July	−14.22	−0.23	0.18	1.01	0.031	0.3
22.L	0900-0930, 25 June	−14.33	−0.21	0.27	1.18	0.098	0.5
23.L	1000-1030, 25 June	−14.73	−0.20	0.28	1.22	0.109	0.5
24.L	0830-0900, 25 June	−15.60	−0.19	0.26	1.10	0.079	0.5
25.L	1000-1030, 26 June	−19.46	−0.15	0.22	0.81	0.042	0.4
26.L	1115-1145, 26 June	−19.49	−0.15	0.24	1.00	0.053	0.6
27.L	1530-1600, 25 June	−19.61	−0.15	0.23	0.93	0.049	0.5
28.L	1000-1030, 27 June	−22.32	−0.13	0.26	1.10	0.059	0.7
29.L	1130-1200, 26 June	−22.81	−0.12	0.25	0.98	0.049	0.6

30.L	1130-1200, 25 June	−23.57	−0.12	0.33	1.25	0.117	0.5
31.L	1700-1730, 20 June	−36.49	−0.07	0.21	0.88	0.019	1.1
32.L	1025-1055, 26 June	−37.23	−0.07	0.29	0.87	0.051	0.4

Table 3. Contribution of the ejection and sweep events at different a.g.l. towards the vertical velocity, air temperature variances and turbulent heat flux. For event identification criteria at different a.g.l. please refer to the text. Since at 200 m a.g.l. no temperature measurements were available the respective columns are empty.

Conditional averaging height, *h*	Contribution to 30 min. period (%)		Contribution to w' variance (%)		Contribution to T_a' variance (%)		Contribution to $w'T_a'$ (%)	
	Ejection	Sweep	Ejection	Sweep	Ejection	Sweep	Ejection	Sweep
8 m a.g.l.	20-25	30-40	30-40	30-40	45-55	25-35	60-70	30-40
45 m a.g.l.	15	20-30	30	30-35	30	25-35	50-60	40-50
200 m a.g.l.	35-40	50-60	25	20	-	-	-	-

Figure captions:

Figure 1. Google Earth view of the experimental sites (Case L and Case S), with the locations of different instruments. 1-hr averaged surface temperatures for 1200-1259 UTC on 27 June, 2011 for Case L and on 2 July, 2011 for Case S are overlaid. Arrangement and measurement heights for different sensors with respect to the typical boundary layer structure are shown on the in-set of the figure.

Figure 2. Spatial behavior of the surface temperature and air temperature (normalized by surface layer temperature scale) at different heights for (a) $L = -6.68$ m at 26 June 0849 UTC and (b) $L = -14.33$ m at 25 June 0921 UTC. The thick white line represents the road, the white circle represents the position of the turbulence measurement tower, and the black line represents the 30 min mean wind direction in the $z = 0$ plane. The thick black vectors represent wind speed at 2, 3, 5 and 8 m a.g.l. (large vector is 2.5 m s^{-1}), and thin black vectors represent vertical velocity normalized by the convective velocity scale (largest vertical vector represents 1 m s^{-1}) in the vertical plane. Please note that the viewing angle for (a) and (b) are different for better visualization as the wind directions are different.

Figure 3. Normalized spectral density ($E_{TT}/(T_*^{SL})^2$) of temperature with height for L = a) -6.68 m and b) -14.33 m. The upper panel (i) shows normalized E_{TT} in the surface layer (both the lower and upper surface layer region) and the lower panel (ii) emphasizes the near-surface region. Since the operating frequencies of the temperature sensors were different at different heights, the regions with missing spectral components are marked white. The lowest available air temperature measurement is marked by a broken white line. (c) Comparison of normalized spectral density at four heights with classical $-5/3$ law for $L = -6.68$ m (without marker) and -14.33 m (with marker).

Figure 4. Normalized temperature standard deviation for air (black circles) and surface (green circles) as a function of stability parameter. The black solid line represents the surface layer similarity theory [15]; the green solid line represents the fitted equation for surface temperature. [50 – 53] and [54] reported σ_T/T_*^{SL} asymptotes to 3 and 6.56 for less unstable boundary layer, i.e. smaller $-z/L$ value.

Figure 5. Evolution of the temperature probability density function with height for L = a) -6.68 m and b) -14.33 m. The upper panel (i) shows the probability density function in the surface layer (both the lower and upper surface layer region)and the lower panel (ii) emphasizes the near-surface. Vertical velocity averaged over each temperature bin is overlaid.

Figure 6. Evolution of ejection events in the near-surface ($z < 0.8$ m, lower panel (ii)) and the lower surface layer ($0.8 \text{ m} < z < 10$ m, upper panel (i)) for L = a) -6.68 m and b) -14.33 m. The colour

scale represents air temperature and black bars (in ii) represents surface temperature (both normalized by the surface layer temperature scale) and black arrows indicate conditionally averaged vertical velocity (largest vector corresponds to 0.42 w_*). The time axis is normalized by the length of individual ejection events such that t = 0, 1 represents the start and end of the ejection event at 8 m a.g.l.

Figure 7. Evolution of the sweep events in the near-surface (z < 0.8 m, lower panel (ii)) and the lower surface layer (0.8 m < z < 10 m, upper panel (i)) for L = a) −6.68 m and b) −14.33 m. The colour scale represents air temperature and black bars (ii) represent surface temperature (both normalized by the surface layer temperature scale) and black arrows indicate conditionally averaged vertical velocity (magnitude of the largest vector corresponds to 0.3 w_*). The time axis is normalized by the length of individual sweep events such that t = 0, 1 represents the start and end of the sweep event at 8 m a.g.l.

Figure 8. Evolution of the a) ejection and b) sweep events in the upper surface layer for L = −6.22 m. The colour scale represents normalized air temperature and the black bars represent normalized surface temperature (both normalized by the surface layer temperature scale) and black arrows indicate conditionally averaged vertical velocity (the largest vectors correspond to 0.75 and 0.4 w_* for ejection and sweep event, respectively). The time axes are normalized by the length of individual ejection and sweep events such that t = 0, 1 represents the start and end of the ejection and sweep event at 45 m a.g.l. for panels (a) and (b) respectively. As described in the beginning of Section 3, a different time period than in Figs. 6-7 had to be used due to data availability.

Figure 9. Evolution of the a) thermals and b) downdraft events in the mixed layer for L = −14.33 m. The time axes are normalized by the length of individual thermals and downdraft events such that t = 0, 1 represents the start and end of the thermals and downdraft event at 200 m a.g.l. for panels (a) and (b) respectively. The colour scale represents vertical velocity normalized by the convective velocity scale, black bars represent surface temperature normalized by the mixed layer temperature scale, and black arrows indicate conditionally averaged vertical velocity.

Figure 10. Evolution of normalized ground heat flux ($G/\langle G \rangle$, solid line, left axes) and normalized turbulent heat flux at 8 m above the ground ($w'T_a'/\langle w'T_a' \rangle$, broken line, right axes) during (i) ejection and (ii) sweep events for L = (a) −6.68 m and (b) −14.33 m. The time axes are normalized by the length of individual ejection and sweep events such that t = 0, 1 represents the start and end of the ejection and sweep event at 8 m a.g.l. for panels (i) and (ii) respectively.