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Surface temperature and surface layer turbulence in a convective boundary layer

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Suggested Reviewers:	Gabriel Katul, PhD Professor, Duke University gaby@duke.edu Conducted ground-breaking study in 1998 on the same topic, albeit limited to a single 'pixel'.
	Christopher Jeffery, PhD Staff Scientist, Los Alamos National Lab cjeffery@lanl.gov Lead Balick et al. study that had similar objectives as our experiment.

	James A Voogt, PhD Professor, University of Western Ontario javoogt@uwo.ca Studied surface temperature fluctuations characteristics in an urban environment.
	Andreas Christen , PhD Assistant Professor, University of British Columbia andreas.christen@ubc.ca Studied surface temperature characteristics in an urban environment
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Surface temperature and surface layer turbulence in a convective boundary layer

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Abstract

Previous laboratory and atmospheric experiments have shown that turbulence influences the surface temperature in a convective boundary layer. The main objective of this study is to examine land-atmosphere coupled heat transport mechanism for different stability conditions. High frequency infrared imagery and sonic anemometer measurements were obtained during the Boundary Layer Late Afternoon and Sunset Turbulence experimental campaign. Temporal turbulence data in the surface layer are then analyzed jointly with spatial surface temperature imagery.

The surface temperature structures are strongly linked to atmospheric turbulence as manifested by several findings. The surface temperature coherent structures move at an advection speed similar to the upper surface layer or mixed layer wind speed with a decreasing trend with stability. Also, with increasing instability the streamwise surface temperature structure size decreases and the structures become more circular. The sequencing of surface and air temperature patterns is further examined through conditional averaging. Surface heating causes the initiation of warm ejection events followed by cold sweep events that result in surface cooling. The ejection events occur about 25% of the time, but account for 60 to 70% of the total sensible heat flux and cause fluctuations of up to 30% in the ground heat flux. Cross-correlation analysis between air and ground temperature confirms the validity of scalar footprint models.

Keywords: Infra-red imagery, Surface layer, Surface layer plumes, Surface temperature.

1. Introduction

The fluid temperature trace in turbulent heat transfer over a flat surface shows the characteristics of periodic activities comprised of alternating large fluctuations and periods of quiescence (Townsend, 1959; Howard, 1966). Sparrow et al. (1970) observed that these periodic activities are due to mushroom-like structures of ascending warm fluid caused by instability due to buoyant forcing (Howard, 1966). Similar structures consisting of ascending warm fluid are also observed in the surface layer of a convective boundary layer (CBL) and known as surface layer plumes. These plumes have diameters on the order of the surface layer height, advection velocities close to the average wind speed over their depth, are tilted by about 45^0 due to wind shear, and are responsible for a majority of total momentum and heat transport (Kaimal and Businger, 1970; Wyngaard et al. 1971; Kaimal et al. 1976; Wilczak and Tillman, 1980; Wilczak and Businger, 1983; Renno et al. 2004). As these plumes ascend through the CBL, they combine with each other to create thermals in the mixed layer.

Conditional averaging of the surface layer plumes by Schols (1984) and Schols et al. (1985) revealed that the resulting air temperature trace shows ramp-like patterns. Gao et al. (1989), Paw U et al. (1992), Braaten et al. (1993) and Raupach et al. (1996) studied these temperature ramp patterns over different canopies and modelled the transport process using the surface renewal (SR) method. The SR method conceptualizes the heat exchange process to occur based on coherent structures: 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. The SR method has been successfully employed to estimate sensible and latent heat flux over different canopies by Paw U et al. (1995), Snyder et al. (1996), Spano et al. (1997, 2000), Castellvi et al. (2002), Castellvi (2004) and Casstellvi and Snyder (2009).

The effect of coherent structures on surface temperature (ST) was first observed by Derksen (1974) and Schols et al. (1985) who found streaky patterns of ST with about a 2 ℃ heterogeneity along the wind direction using an airborne thermal infra-red (IR) camera. Hetsroni and Rozenblit (1994), Hetsroni et al. (2001), and Gurka et al. (2004) observed a similar streaky structure of ST in a laboratory convective water flume experiment at different Reynolds numbers. High ST streaks corresponded to low velocity fluid streaks in the boundary layer and the distance between streaks increased with Reynolds number. Using an IR temperature sensor Paw U et al. (1992), Katul et al. (1998) and Renno et al. (2004) observed ST fluctuations in the CBL with an amplitude of 0.5 ℃ over 2.6 m high maize crops, greater than 2 ℃ over 1 m high grass, and 2-4 ℃ over a desert area, respectively. Using IR imagery, Ballard et al. (2004), Vogt (2008) and Christen et al. (2012) observed spatial heterogeneities in the magnitude of ST fluctuations over a grass canopy, a bare field, and in an urban environment, respectively.

Direct numerical simulation of turbulent heat transfer coupled with heat conduction in the adjacent solid by Tiselj et al. (2001) revealed that the magnitude of ST fluctuation depends on the wall thickness and relative strength of thermal response times for the solid and fluid. Balick et al. (2003) identified similar key parameters for the coupled heat transfer process at the earth's surface. Ballard et al. (2004) hypothesized that high frequency ST fluctuations are caused by turbulent mixing. Katul et al. (1998) and Renno et al. (2004) argued that ST fluctuations are caused by inactive eddy motion and convective mixed layer processes. Christen and Voogt (2009, 2010) visualized the spatial ST field in a suburban street canyon and qualitatively attributed the vertical heat transport to the observed coherent structures that were shown to move along the wind direction.

Garai and Kleissl (2011) examined ST structures and heat transport processes over an artificial turf field using 1 Hz IR imagery. Although the camera footprint was smaller (48 m x 15 m) than the scale of the largest ST structures, different ST characteristics were identified corresponding to different phases of the SR process. The ST field 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. Sequential animation of the ST showed growth and merging of thermal footprints as they move along the wind direction. The main objective for the experimental setup was to address the main limitation of Garai and Kleissl (2011) and resolve the largest ST structures by increasing the mounting height of the IR camera. Furthermore turbulence measurements were collocated at different heights that allowed further investigating the cause and manifestation of ST structures as a function of atmospheric stability and the interaction between thermal footprints and lower surface layer turbulence. In Sections 2, 3, and 4 we will describe the experimental setup, results, and discussion and conclusions, respectively.

2. Experiment and data processing

a. Experimental setup

The experiment was conducted in collaboration with Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST; Lothon et al., 2012) field campaign at Centre de Recherches Atmosphériques, Lannemezan, France from 14 June to 8 July, 2011 (Figure 1). ST data at 1 Hz were captured by a FLIR A320 Thermal IR camera. It was mounted 59 m above ground level (a.g.l.) at the 60 m tower (43°07'25.15" N, 0°21'45.33" E) looking towards 55° N with an inclination of 2° from 16 June to 29 June, 2011. It overlooked a 9 cm high grass field with an albedo of 0.19. Longwave radiation (8 − 14 μm wavelength) from the surface was measured in 240 x 320 pixels and converted into ST (T_s) assuming an emissivity of 0.95 (Oke, 1987). The accuracy of the camera is 0.08 K. A coordinate system transformation and interpolation was performed to transform the original image to a cartesian coordinate system. This resulted in a camera footprint of 450 m x 207 m with a uniform resolution of 4.5 m x 0.65 m. A 1 hr daytime average of the ST from the IR camera (overlaid on a map in Figure 1) shows road, buildings and bare soil regions to be warmer and a small pond to be cooler than the grass regions.

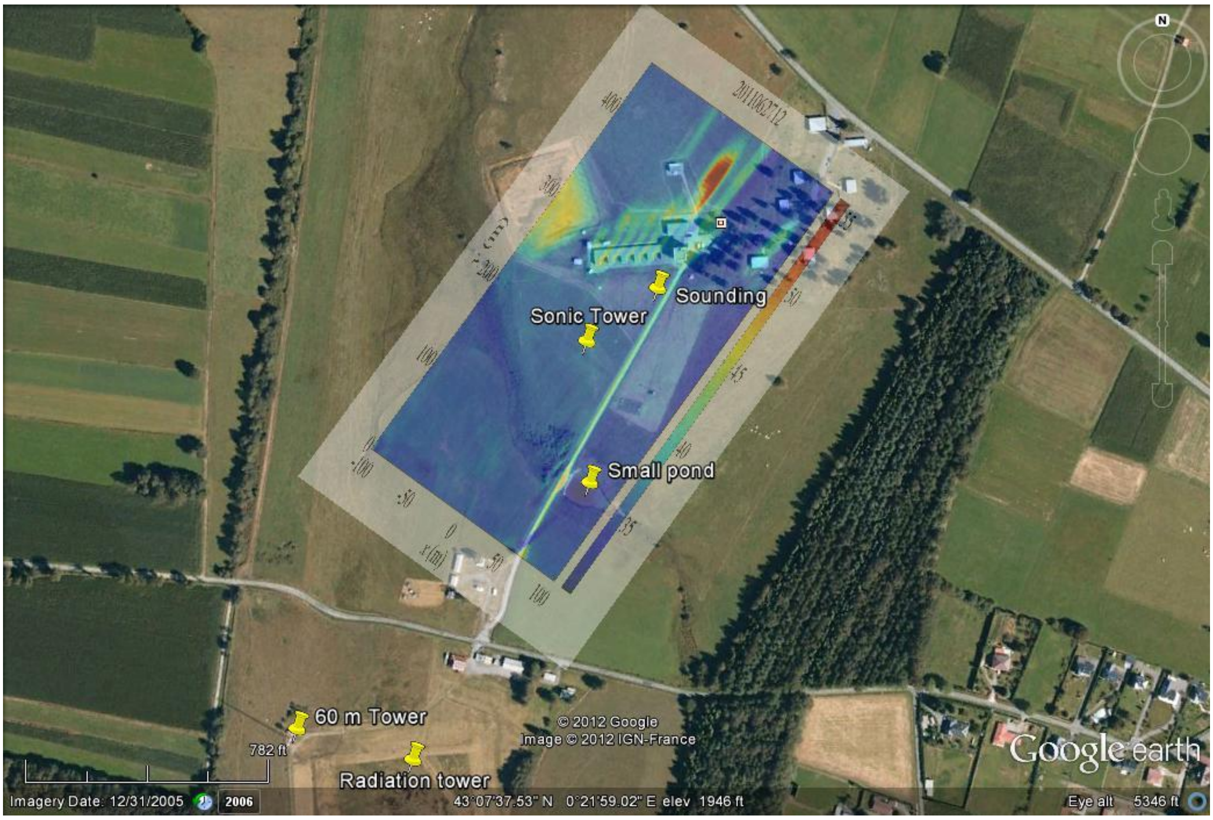


Figure 1. Google Earth map of the experimental site. The locations of the 10 m sonic anemometer tower, 60 m tower, radiation tower, and release position of radiosondes are marked. 1-hr averaged ST as viewed from the 60 m tower at 1200 - 1259 UTC (1400 -1459 local time) on 27 June, 2011 is overlaid. The quantitative analysis considers only the area of $y < 275$ m.

Four Campbell Scientific Sonic Anemometer-Thermometers (CSAT) measured turbulent velocity (u, v, w) and sonic air temperature (AT, T_a) at 20 Hz at 2.23 m, 3.23 m, 5.27 m and 8.22 m a.g.l. inside the camera footprint at 43°07'39.2" N, 0°21'37.3" E ("Sonic Tower" in Fig. 1). Hereinafter these CSATs will be referred to as 2 m, 3 m, 5 m and 8 m CSATs. The CSATs were pointing towards 60° N. A coordinate system rotation was conducted to ensure $|\langle w \rangle / M| < 1\%$ (angled brackets denote temporal averaging and M is the horizontal wind speed) and to orient the CSAT winds into the IR-camera coordinate system following Wilczak et al. (2001).

Radiosondes were released at 43°07'41" N, 0°22'01" E ("Sounding" in Fig. 1) every 6 hours until 25th June, 2011 and every 3 hours thereafter providing profiles of wind speed, direction, temperature, humidity up to 20 km with a vertical resolution of 5 m.

A radiation tower at 43°07'26" N, 0°21'50.4" E near the 60 m tower (Figure 1) was equipped with Kipp & Zonen CM22 and CM21 pyranometers to measure the shortwave up- and down-welling irradiances, and an Eppley-PIR and a Kipp & Zonen CG4 pyrgeometers to measure the longwave up- and down-welling irradiance respectively. All radiation measurements were reported as 1 min averages.

All measurement platforms were GPS synchronized to Coordinated Universal Time (UTC), which lags local time by 2 hours.

b. Data processing

Ogive tests (Foken et al., 2006) revealed that an averaging period of 5-min is sufficient to estimate momentum and heat fluxes from the 2 m to 8 m CSATs using the eddy covariance method (for details see Appendix). To minimize the effects of changing meteorological conditions on the fluctuating time series of wind speed (u, v, w), AT (T_a), and ST (T_s) the 5-min linear trend was removed using:

$$X' = X(t) - \left(\langle X \rangle_{5min} - a_{X,5min} t\right), \tag{1}$$

where $a_{X,5min}(t)$ is the linear time dependence coefficient of variable X (for ST, $a_{ST,5min}(t, x, y)$, i.e. it is computed separately for each camera pixel). Since, there were no continuously functioning finewire thermocouples or infra-red gas analyzers on the Sonic tower, the kinematic sensible heat flux was estimated using $\frac{H}{\rho_a c_{p,a}} \approx \frac{\langle w' T_a' \rangle}{(1+{}^{0.06}/_{B})}$, where ρ_a, $C_{p,a}$ and B are the dry air density, dry air specific heat and the Bowen ratio estimated using a CSAT and a LICOR 7500A CO_2/H_2O analyzer mounted at 29.3 m a.g.l. at the 60 m tower, operated at 10 Hz, and taking an averaging period of 10 min. The 2 m CSAT data was used to estimate mean sensible heat flux (H), friction velocity $u_* = (\langle u'w' \rangle^2 + \langle v'w' \rangle^2)^{1/4}$, convective velocity $w_* = \left(\frac{g z_i}{\langle T_a \rangle} \frac{H}{\rho_a c_{p,a}}\right)^{1/3}$, surface layer temperature scale $T_*^{SL} = -\frac{\frac{H}{\rho_a c_{p,a}}}{u_*}$, Obukhov length $L = -\frac{\langle T_a \rangle u_*^3}{\kappa g \frac{H}{\rho_a c_{p,a}}}$ and flux Richardson number $Ri_f = \frac{\frac{g}{\langle T_a \rangle} \frac{H}{\rho_a c_{p,a}}}{u_*^2 \frac{\partial \langle M \rangle}{\partial z}}$, where κ and g are von Karman constant and gravitational constant respectively. The vertical gradient of horizontal wind speed was estimated using Businger-Dyer similarity relationships.

Footprint functions estimate the relative contribution of scalar sources from different ground locations to the measurement location of the scalar. To calculate footprints of different CSATs, we used the scalar footprint derived from the flux footprint model by Hsieh et al. (2000). In this model the 1-D flux footprint function (f) for the unstable boundary layer is

$$f(\tilde{x}, z_m) = \frac{1}{\kappa^2 \tilde{x}^2} 0.28 z_u^{0.59} |L|^{1-0.59} \exp\left(\frac{-1}{\kappa^2 \tilde{x}} 0.28 z_u^{0.59} |L|^{1-0.59}\right), \tag{2a}$$

where $\tilde{x}$, z_m and z_u are streamwise distance from the measurement tower, measurement height and a scaled measurement height defined as $z_u = z_m\left(\log\left({}^{z_m}/_{z_o}\right) - 1 + {}^{z_o}/_{z_m}\right)$, where z_o is the roughness height. The flux footprint (f) is related to scalar footprint (C) by (Kormann and Meixner, 2001)

$$M\frac{\partial C}{\partial \tilde{x}} = -\frac{\partial f}{\partial z}. \tag{2b}$$

The 1-D scalar footprint function (C) was then used to calculate the 2-D scalar footprint function (C_{2D}) assuming a Gaussian distribution of zero mean and standard deviation of the wind direction (σ_θ) using

$$\sigma_{\tilde{y}} = \frac{\sigma_\theta \tilde{x}}{1+\sqrt{\frac{\tilde{x}}{400\langle M\rangle}}},$$

$$C_{2D} = \frac{C}{\sqrt{2\pi}\sigma_{\tilde{y}}} e^{-\frac{\tilde{y}^2}{2\sigma_{\tilde{y}}^2}}, \tag{2c}$$

where $\tilde{y}$ is spanwise distance. For the comparison of 20 Hz turbulence data with 1 Hz footprint averaged ST data, a box filter of size 1 s centred at the time stamp of ST was applied.

Net radiation R_{net} was obtained from the radiation tower measurements, but up-welling longwave irradiance measured at the radiation tower was replaced by the average IR-camera measurement.

Finally, the surface heat flux G was modelled numerically by solving the transient 3-D heat conduction equation:

$$\frac{\partial T_g}{\partial t} = \alpha_g\left(\frac{\partial^2 T_g}{\partial x^2} + \frac{\partial^2 T_g}{\partial y^2} + \frac{\partial^2 T_g}{\partial z^2}\right), \tag{3a}$$

where α_g and T_g are the thermal diffusivity and the temperature of the soil respectively. The conduction equation was discretized horizontally using a spectral method with periodic boundary conditions; vertically a second order finite difference scheme was used; the Euler implicit scheme was applied for time integration. The numerical solution of Eq. 3a was validated against the analytical solution of constant and sinusoidal varying surface temperature (not shown). To simulate soil temperatures, homogeneous clay soil with 40% volumetric water content was assumed yielding thermal diffusivity α_g and conductivity k_g of 0.4 $mm^2\ s^{-1}$ and 0.8 $W\ m^{-1}\ K^{-1}$ respectively (Campbell and Norman, 1998). The IR temperature (T_s) was used as top-surface boundary condition (z = 0 m), an adiabatic boundary condition ($\frac{\partial T_g}{\partial z} = 0$)was used as the bottom boundary condition (z = -5.5 m) and the temperature in the domain was initiated by $T_g(x,y,z,t=0) = T_\infty + \frac{\langle G\rangle}{k_g}\left\{2\left(\frac{\alpha_g \tau}{\pi}\right)^{1/2}\exp\left(-\frac{z^2}{4\alpha_g\tau}\right) + \frac{z}{2}\operatorname{erfc}\left(-\frac{z}{2\sqrt{\alpha_g\tau}}\right)\right\}$, where $\langle G\rangle$ $(= R_{net} -$

$\left(1+\frac{1}{B}\right)H$) is the mean surface heat flux obtained from the surface energy balance, τ ($=\left[\frac{k_g(\langle T_s\rangle - T_\infty)}{2\langle G\rangle}\right]^2 \frac{\pi}{\alpha_g}$) is a dummy time variable to ensure minimal unrealistic initialization effect (Carslaw and Jaeger, 1959), T_∞ (= 288 K) is the soil temperature at $z \to -\infty$ (corresponding to the annual average air temperature) and erfc is complimentary error function. As the temperature gradient is strongest near the surface, the vertical grid resolution was set to 1.5 mm; below z = -0.05 m the vertical grid was stretched uniformly to 0.1 m resolution. The simulation was spun up for 100 time steps to limit the influence of the initial conditions. The heat flux at the surface was then computed from T_g as:

$$G = \left[\frac{\Delta z}{2\Delta t}\int_{\Delta t} \rho_g C_{p_g} \frac{\partial T_g}{\partial t} dt\right] - \left[\frac{\Delta z}{2\Delta x}\int_{\Delta x} k_g \frac{\partial^2 T_g}{\partial x^2} dx + \frac{\Delta z}{2\Delta y}\int_{\Delta y} k_g \frac{\partial^2 T_g}{\partial y^2} dy\right] + \left[k_g \frac{T_s - T_{g,-\Delta z}}{\Delta z}\right], \quad (3b)$$

where ρ_g, C_{pg}, Δx, Δy, Δz are density, specific heat of the soil and grid size in horizontal (x, y) and vertical (z) directions respectively. In Eq. 3b the first, second and third bracketed terms represent temporal storage, horizontal heat diffusion and vertical heat diffusion respectively.

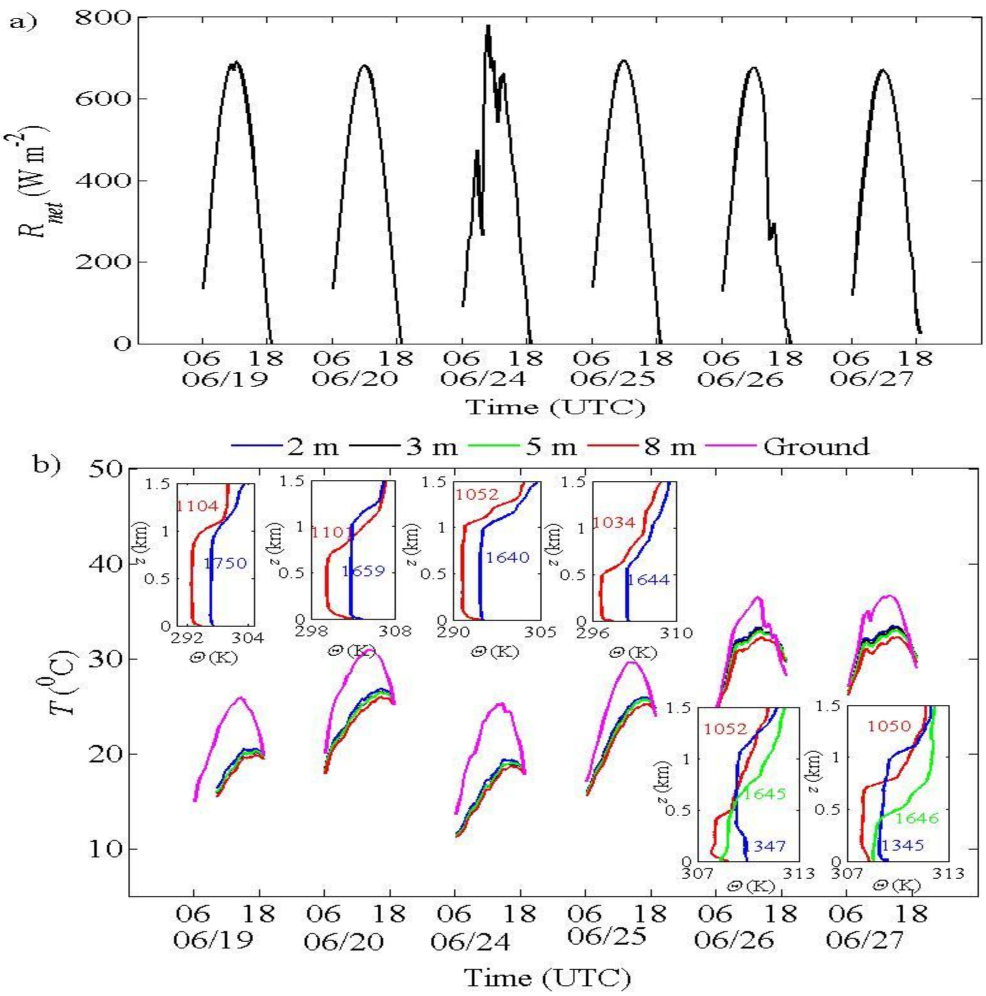
3. Results

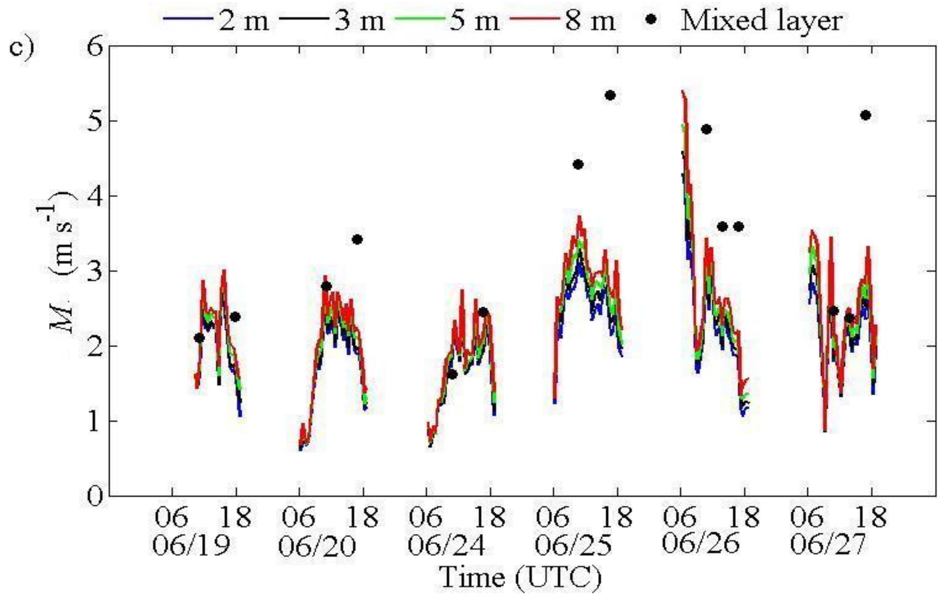
Since ST fluctuations exceed the noise level of the camera only during unstable conditions (Garai & Kleissl 2011), only daytime data were considered for detailed analysis. Building (y > 275 m) and road (a straight line from x = 65 m at y = 0 m to x = 30 m at y = 300 m) pixels (Fig. 1) in the IR images were omitted from the analysis, to minimize effects of surface heterogeneity.

a. Meteorological conditions

Figure 2 presents 30-min averaged meteorological conditions for the intensive observational periods consisting of the clear days during 16 to 27 June, 2011. Potential temperature from radiosonde data are shown in the inset of the figures. Clear days are expected to produce both stationary time periods and the most unstable stability conditions. R_{net} reaches up to 700 W m^{-2} during midday for all clear days. There were some early morning and late afternoon clouds on 24 and 26 June, respectively. Rain (about 2-2.5 mm) occurred on 18 and 22-23 June as cold low pressure systems from the Atlantic Ocean crossed the site. AT dropped to 15-20 ^{0}C just after the rain and increased on successive clear days. ST followed a similar trend as AT. Potential temperature (Θ) profiles from radiosondes show that the inversion height (z_i) did not exhibit a strong diurnal cycle except on 20, 26 and 27 June. It was about 1 km for 19 and 24 June and 600 m for 25 June. It increased from 750 m to 1 km on 20 June, increased from 500 m to 1 km and then dropped to 750 m on 26 June and increased from 750 m to 1 km and then dropped to 450 m on 27 June for the 1050, 1350, and 1650 UTC soundings, respectively. The near surface wind speed was about 2.5 m s^{-1} for 19, 20 and 24 June and about 3 m s^{-1} for 25 to 27

June. Mixed layer wind speed (the mean of radiosonde data from z/z_i = 0.1 to 0.8) was close to the 8 m wind speed for all days except 25 and 26 June, when the mixed layer wind speed was at least 25% larger. Wind direction was northerly for 19 and 24 June, easterly for 25 and 26 June and north-easterly for 20 and 27 June. Easterly to north-easterly wind is typical for the mountain-plain circulation in the area.





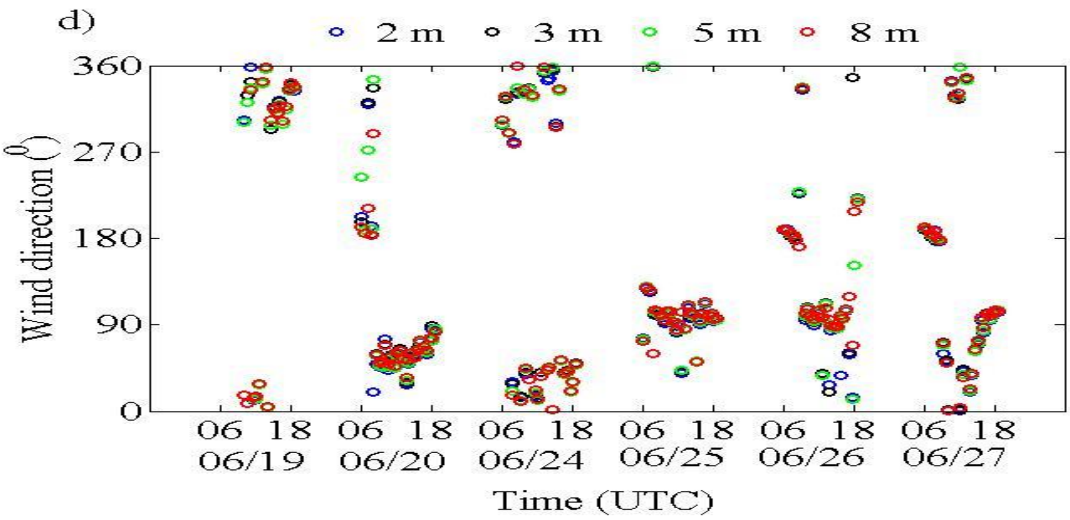


Figure 2. 30-min averages of (a) net radiation, (b) temperatures, (c) wind speed and (d) wind direction. Radiosonde potential temperature profiles are shown in the inset of (b), where the release time (HHMM UTC) is shown in colour.

Thirty minute periods were chosen for further investigation based on the following stationary criteria applied to the 2 m CSAT data: constant Obukhov length and wind speed (standard deviation of the six 5 min means within a half hour less than 10% of the mean) and constant wind direction (standard deviation of the six 5 min vector means less than 20^0). Data from the days after the rain (19 and 24 June) are excluded, as the IR surface temperature is affected by local pooling of water. Stationary periods are characterized in Table 1 in order of increasing stability. The gradient Richardson number is strongly correlated with the stability parameter, $\zeta = z/L$ (Businger et al. 1971), which in turn is related to the flux Richardson number by the ratio of turbulent diffusivity of heat and momentum for unstable boundary layers. The data from the 2 m CSAT, indicate that $Ri_f = 1.69\zeta$ with

99.7% coefficient of determination, where ζ = 2.23 m/L. Thus, either ζ or Ri_f can be used to investigate the impact of stability on the different turbulent statistics. For the remainder of the paper stability will be parameterized by ζ.

Table 1. Scales, stability and turbulence parameters sorted by L and Ri_f during periods classified as stationary (see text for criteria used). Inversion heights z_i were estimated visually from the radio soundings as inflection point in the potential temperature profiles (increase in potential temperature exceeds 1 K over 100 m height).

Time (UTC)	L (m)	Ri_f (-)	u_* (m s^{-1})	w_* (m s^{-1})	$\frac{H}{\rho_a c_{p,a}}$ (K m s^{-1})	z_i (km)
0930-1000, 27 June	-5.49	-0.66	0.15	0.95	0.045	0.6
0830-0900, 26 June	-6.68	-0.52	0.15	0.71	0.028	0.4
1100-1130, 20 June	-7.27	-0.47	0.22	1.38	0.113	0.7
1100-1130, 27 June	-8.45	-0.39	0.19	1.15	0.058	0.8
1030-1100, 27 June	-8.45	-0.39	0.18	1.06	0.053	0.7
1530-1600, 20 June	-8.84	-0.37	0.19	1.31	0.062	1.1
0935-1005, 26 June	-9.40	-0.35	0.17	0.82	0.043	0.4
0825-0855, 27 June	-10.22	-0.31	0.15	0.76	0.027	0.5
1200-1230, 25 June	-11.74	-0.27	0.26	1.23	0.112	0.5
1030-1100, 25 June	-12.49	-0.25	0.27	1.23	0.112	0.5
0900-0930, 25 June	-14.33	-0.21	0.27	1.18	0.098	0.5
1000-1030, 25 June	-14.73	-0.20	0.28	1.22	0.109	0.5
0830-0900, 25 June	-15.60	-0.19	0.26	1.10	0.079	0.5
1000-1030, 26 June	-19.46	-0.15	0.22	0.81	0.042	0.4
1115-1145, 26 June	-19.49	-0.15	0.24	1.00	0.053	0.6
1530-1600, 25 June	-19.61	-0.15	0.23	0.93	0.049	0.5
1000-1030, 27 June	-22.32	-0.13	0.26	1.10	0.059	0.7
1130-1200, 26 June	-22.81	-0.12	0.25	0.98	0.049	0.6
1130-1200, 25 June	-23.57	-0.12	0.33	1.25	0.117	0.5
1700-1730, 20 June	-36.49	-0.07	0.21	0.88	0.019	1.1
1025-1055, 26 June	-37.23	-0.07	0.29	0.87	0.051	0.4

b. Spatial and temporal evolution of surface and air temperatures and comparison to similarity functions

We have chosen the time periods with L = -10.22 m and -19.49 m to illustrate stability dependence, as they are representative of more unstable and less unstable conditions in our dataset and of different wind directions (177° for L = -10.22 m and 91° for L = -19.49 m). Structures in the spatial ST fluctuation field are aligned with the wind direction (Fig. 3) demonstrating that the observed ST structures are not an artifact of surface heterogeneity or topography (since temporal averages have been removed as in Eq. 1). With time these ST structures grow, merge with each other, and move along with the wind (not shown).

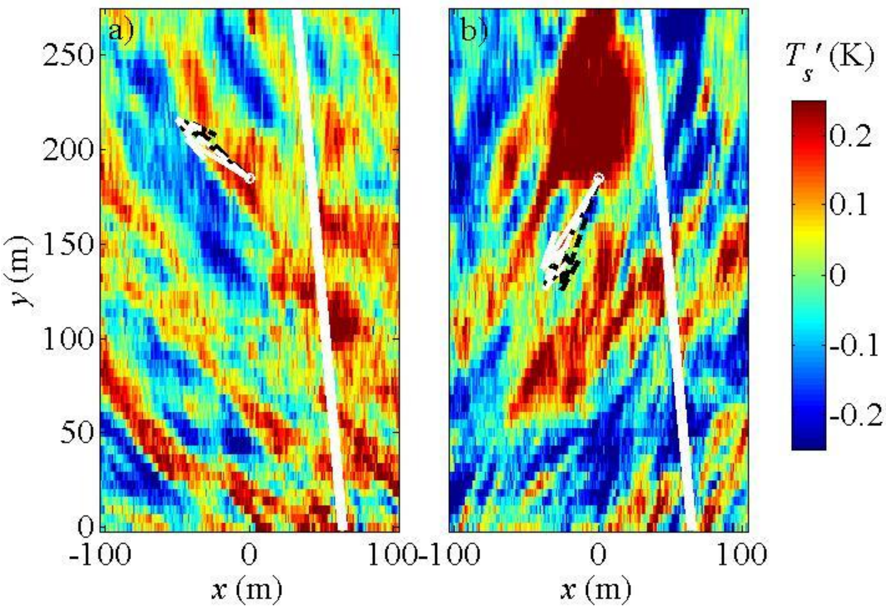


Figure 3. Snapshots of ST fluctuations for L = a) -10.22 m at 27 June 0838 UTC, and b) -19.49 m at 26 June 1124 UTC. Lines represent 1 s averaged wind vectors (scaled to the distance covered in 25 sec) at 8 m (black solid), 5 m (black dashed), 3 m (white solid) and 2 m (white dashed) a.g.l. at the measurement location (white circle) respectively. The thick white line represents data excluded due to the road.

The temporal evolutions of ST and AT fluctuations at different heights are then compared in Fig. 4. The ST is the average across the scalar footprint (Eqs. 2) of the 2 m CSAT with a cut-off of 10% of the maximum value of the scalar footprint function. Fig. 4 shows that AT and STs are highly cross-correlated and AT lags ST since the footprint is upstream: when the surface is cold the air starts to cool and when the surface is warm the air starts to warm. Also, the AT at a lower altitude shows more small scales compared to the ST. This is due to the fact that the ST is spatially averaged across the footprint and not as affected by small scales as the surface has larger thermal mass. Comparing Figs. 4a and 4b reveals that both ST and AT show more small scale fluctuations as the boundary layer becomes more unstable. Similar results are obtained for all other stationary conditions.

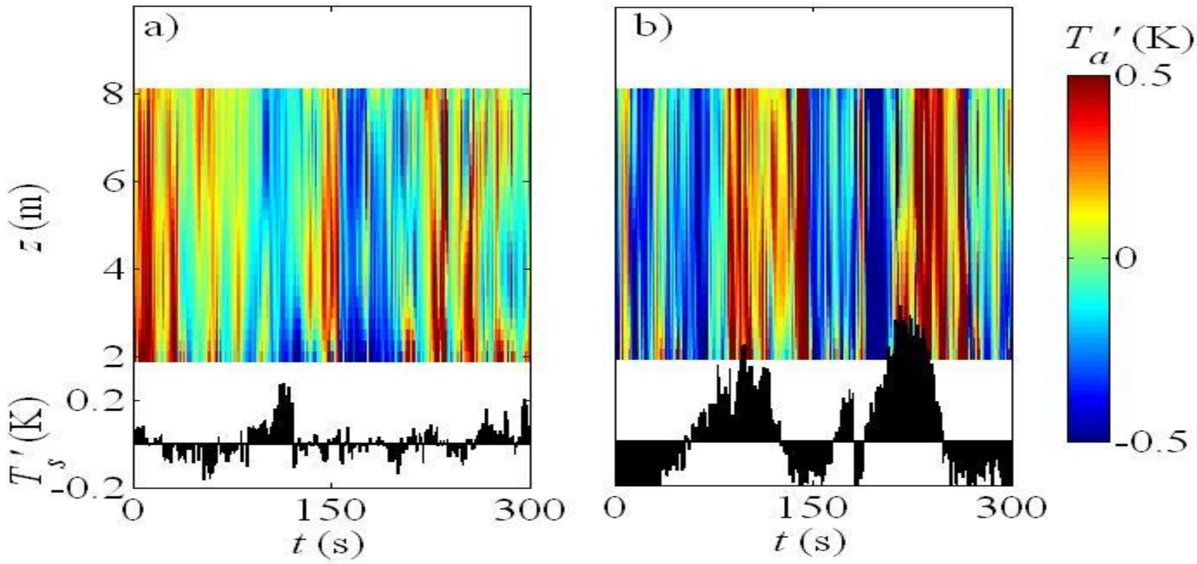


Figure 4. Time series of AT (colour bar) and footprint-averaged ST (bar plot) for L = a) -10.22 m at 27 June 0833-0838 UTC and b) -19.49 m at 26 June 1122-1127 UTC. ATs were vertically interpolated using spline interpolation. The footprint is the area with greater than 10% of the maximum value of the scalar footprint function of the 2 m CSAT.

Figure 5 shows temperature standard deviations normalized by the surface layer temperature scale, T_*^{SL}, for all stationary periods. Normalized σ_{Ta} for 2 and 8 m a.g.l. decrease with increasing height and stability closely following the surface layer similarity theory, ${\sigma_{Ta}}/{T_*^{SL}} = -0.95\left(-{z}/{L}\right)^{-1/3}$ (Wyngaard et al., 1971). σ_{Ts} is smaller than σ_{Ta} at 8 m a.g.l. and can be fit as ${\sigma_{Ts}}/{T_*^{SL}} = -0.36(-\zeta)^{-0.39}$. Direct numerical simulations of the solid-fluid coupled turbulent heat transfer without buoyancy forcing term by Tiselj et al. (2001) showed that σ_{Ts} depends on the solid thickness and the thermal properties of solid and fluid. They have characterized this phenomenon by the thermal activity ratio, $TAR = \frac{k_a}{k_g}\sqrt{\frac{\alpha_g}{\alpha_a}}$, where k_a and α_a are thermal conductivity and thermal diffusivity of fluid. They found that a fluid-solid combination with low *TAR* does not allow imprints of fluid temperature fluctuation on the solid surface. Balick et al. (2003) also found a similar parameter for a coupled land-atmosphere heat transfer model. For our measurement site, assuming k_a = 0.025 W m^{-1} K^{-1} and α_a = 20 mm^2 s^{-1} and homogeneous clay soil with 40% volumetric water content, *TAR* = 0.0044. Under these conditions according to Tiselj et al. (2001) σ_{Ts} would be less than 1% of its iso-flux counterpart that corresponds to $TAR \rightarrow \infty$. Though our measurements seem to overestimate σ_{Ts}, field experiment and DNS cannot be directly compared since the DNS simulation ignored buoyancy term in the Navier-Stokes equations.

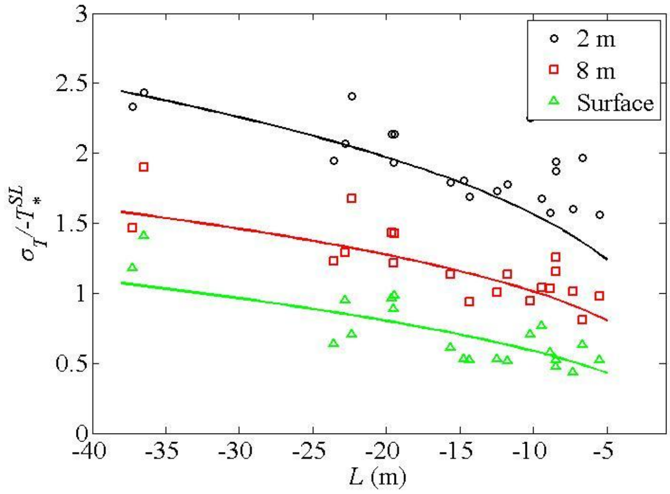


Figure 5. Normalized variance of ST and AT as a function of L. The markers are measurements for the periods in Table 1, the black and red solid lines are fitted according to the surface layer similarity theory $^{\sigma_{Ta}}/_{T_*^{SL}} = -0.95\left(-^{z}/_{L}\right)^{-1/3}$ and the green line is the fit to the ST fluctuation: $^{\sigma_{Ts}}/_{-T_*^{SL}} = 0.36(-\zeta)^{-0.39}$.

c. Spatial scale of surface temperature structures

The spatial scale of ST structures (as seen in Fig. 3) was then studied by considering the spatial correlation for each image using $\rho_{xy}(\Delta x, \Delta y, t) = \frac{\overline{T_s'(x,y,t)T_s'(x+\Delta x, y+\Delta y, t)}}{\sigma_{Ts}^2}$, where the overbar indicates a spatial average. Figure 9 shows the temporal average of the spatial correlation of the ST structures ($\rho_{xy}(\Delta x, \Delta y) = \langle \rho_{xy}(\Delta x, \Delta y, t) \rangle$) for L = (a) -10.22 m, and (b) -19.49 m. The ST correlation structures are shaped as ellipsoids with the major axis aligned with the streamwise direction.

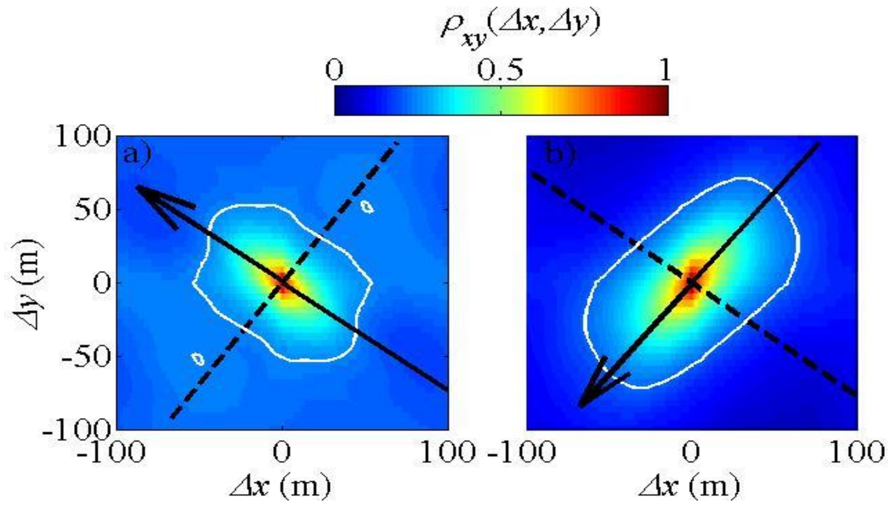


Figure 6. Mean spatial correlation of ST for L = (a) -10.22 m, and (b) -19.49 m (in the camera coordinate system). The solid and broken black lines indicate averaged streamwise and spanwise directions over 2, 3, 5 and 8 m a.g.l., respectively. The white contour line indicates a correlation of 0.25.

The spatial properties of coherent structures in a boundary layer flow depend on the shear and the buoyancy. For a shear dominated boundary layer, the structures become elongated in the wind direction and streaky, whereas for a buoyancy dominated boundary layer, they become more circular. We consider u_* as a measure of shear and ζ as a measure of relative strength of buoyancy over shear to study their effect on the ST structures. Figure 7 shows (i) the streamwise correlation length (l_{stream}) and (ii) the aspect ratio ($AR = l_{stream}/l_{span}$, where l_{span} is the spanwise correlation length) against ζ and u_* for all stationary periods. The correlation length is defined as twice the distance from the centre where the correlation becomes 0.25 in the streamwise and spanwise directions (Fig. 6). With increasing stability the structures become longer. Thus the AR is close to unity for the more unstable cases and larger than unity for the less unstable cases. l_{stream} does not show any recognizable trend against u_*, but the AR increase from 1.5 for small u_* to more than 2 for larger u_*. Wilczak and Tillman (1980) reported similar streamwise sizes of coherent structures based on the time traces of AT at 4 m a.g.l..

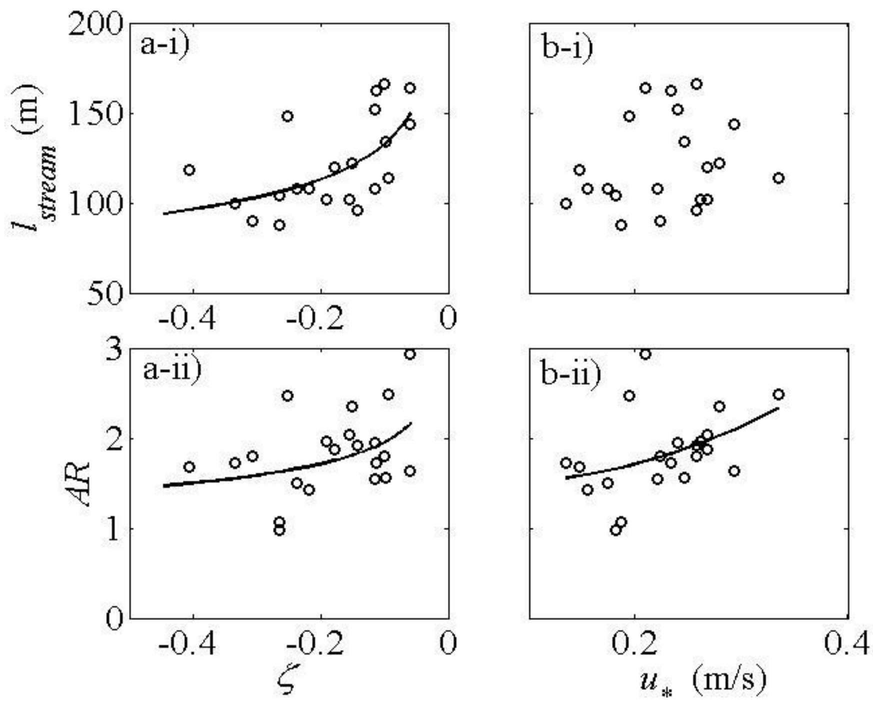


Figure 7. (i) Streamwise correlation length l_{stream} and (ii) aspect ratio AR of the mean ST structure with (a) ζ and (b) u_*. Markers represent the measurements and solid lines represent fits: $l_{stream} =$

$78.03(-\zeta)^{-0.23}, AR = 1.26(-\zeta)^{-0.19}, AR = 11.43u_*^2 - 1.5u_* + 1.55$ with 48.6%, 28.0% and 27.7% coefficient of determination respectively. No trend was observed and no line was fit for b-i.

d. Surface and air temperature correlation

Since the footprint-averaged ST is correlated with AT (Fig. 4), spatial maps of cross-correlation between ST and AT were generated using $\rho_{Ts,Ta}(x,y,\Delta t) = \frac{\langle T_s'(x,y,t) T_a'(x_o,y_o,t+\Delta t)\rangle}{\sigma_{Ts}\sigma_{Ta}}$, where x_o and y_o are the coordinates of the sonic tower and the two vectors are lagged by up to Δt =60 sec. To reduce noise in the cross-correlation maps, an ensemble average of three cross-correlation maps for each 10 min interval in a 30 min stationary period was computed. Spatial maps of maximum cross-correlations between ST and AT at (i) 2 m and (ii) 8 m a.g.l. are shown in Fig. 8. The region of maximum cross-correlation between ST and AT is aligned with the wind. The upwind correlation region and the scalar footprint function show significant overlap (however, note the footprint obviously only extends upwind while the correlation extends upwind and downwind). Specifically, the cross-wind spread for the maximum correlation region is similar to that of the footprint function which was modelled by a Gaussian distribution with a standard deviation of the wind direction (Eq. 2c). The maximum correlation coefficient, size of the correlation region, and the footprint increase when the 8 m AT is correlated with the ST. Similar trends are also observed for the other stationary periods.

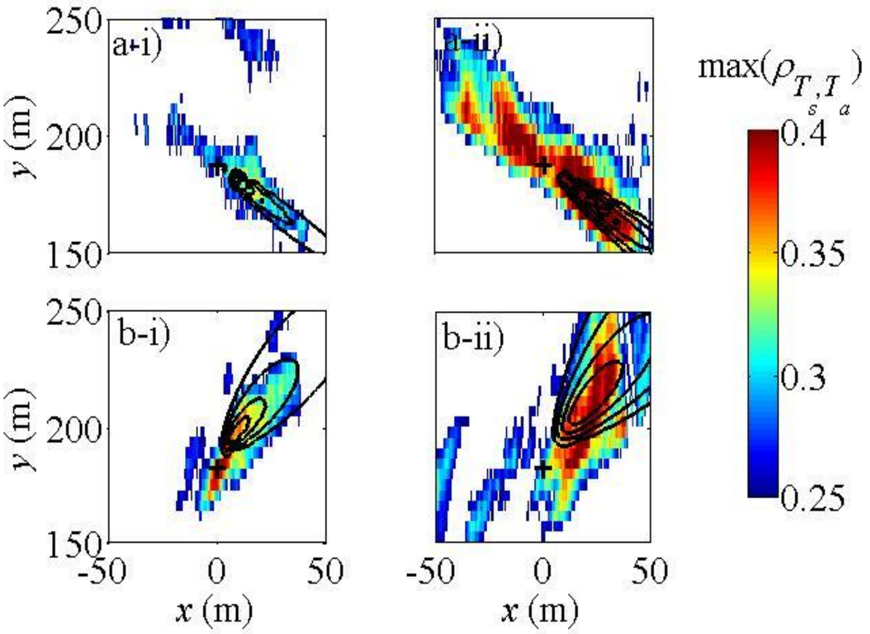


Figure 8. Thirty minute maximum cross-correlation between ST and AT at (i) 2 m and (ii) 8 m with scalar footprint model (black contours) for L = (a) -10.22 m, and (b) -19.49 m. White pixels represent

ST-AT correlation less than 0.25 or unreasonable lags (absolute lag greater than 60 s). The black contour line represents 10, 25, 50 and 75% of the maximum of scalar footprint function. The black + sign marks the location of the sonic tower (x_o = 0.4 m and y_o = 185 m).

Along the wind direction cross-correlations between the AT at 8 m a.g.l. and the lagged ST (Figs. 8-ii) are then plotted in Figs. 9-i. Here, positive r indicates the downwind direction and positive lags indicate that the surface is preceding the air and vice versa. The largest cross-correlations for the upwind (downwind) correlation region occur at a positive (negative) lag (shown in Figs. 9-i). Thus the upwind ST is affecting the AT at the measurement location and the AT at the measurement location is affecting the downwind ST, consistent with Garai and Kleissl (2011). Cross-correlations between ST along the wind direction are shown in Figs. 9-ii as calculated using $\rho_{Ts,Ts}(r,\Delta t\colon x_*,y_*) = \frac{\langle T_S{}'(x_*+r\cos\theta, y_*+r\sin\theta, t+\Delta t)T_S{}'(x_*,y_*,t)\rangle}{\sigma_{Ts}^2}$, where x_*, y_* and θ are arbitrary coordinates in the image and wind direction. To reduce the noise of the ST-ST cross-correlation, ensemble averages from 15 different (x_*, y_*) positions were computed. Note the distinction between these cross-correlations versus the spatial correlations $\rho_{xy}(\Delta x, \Delta y, t)$ described in Section 3c; the former 'tracks' ST structures by co-varying space (r) and time (Δt), while the latter correlates structures that are not time shifted across space. Therefore, $\rho_{xy}(\Delta x, \Delta y, t)$ represents the typical spatial extent of ST structures at a given time and $\rho_{Ts,Ts}(r,\Delta t\colon x_*,y_*)$ represents the spatio-temporal region of influence of a given structure. If a structure remained unchanged as it moves across the image, $\rho_{Ts,Ts}(r,\Delta t\colon x_*,y_*)$ would be large.

For ST-ST correlations, a positive lag indicates that the upwind ST is preceded by downwind ST. The value of ST-ST cross-correlations in Figs. 9-ii are larger compared to AT-ST cross-correlations in Fig. 9-i as the latter is calculated between two different variables and heights. Since the spatial extent of the AT-ST region of large correlation depends on the AT measurement height, it is not useful to compare quantitatively the spatial extent of the high correlation region for AT-ST and ST-ST at a given stability. Qualitatively, as the stability of the boundary layer increases, the spatial extent of high AT-ST and ST-ST correlation region increases. A less unstable boundary layer will contain longer turbulence structures which is manifested in the larger footprints in Fig. 9-i. The AT-ST ad ST-ST correlation graphs allow tracking the advection speed of the structures responsible for land-atmosphere exchange.

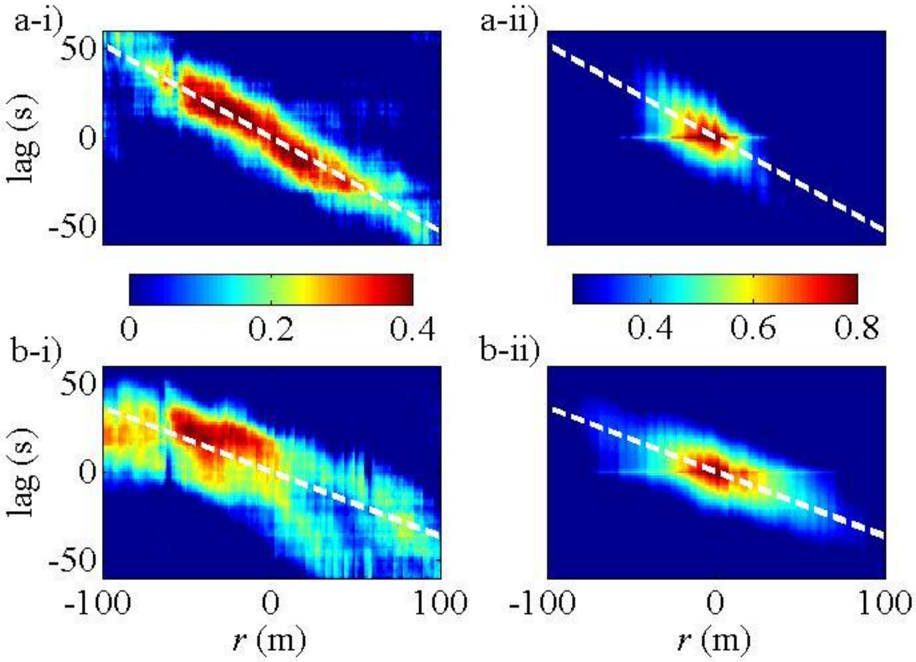


Figure 9. Left panels: Cross-correlation between AT at 8 m with ST along the 8 m wind direction at different lags. Right panels: Cross-correlation amongst STs along the 8 m wind direction at different lags. (a) L = -10.22 m, and (b) L = -19.49 m. The white dashed line represents the slope of the cross-correlation area.

e. Advection speed of the surface temperature structures

The slopes of AT-ST and ST-ST temperatures cross-correlation surfaces show similar values for a given stationary period, thus signifying the advective nature of the surface temperature coherent structures. Hence, the slope of the cross-correlation in the lag-distance plot (Fig. 9) indicates the advection speed u_s of the ST structures (or rather the turbulent coherent structures that leave an imprint on the surface) along the wind direction. The estimated advection speeds for all stationary periods are plotted in Fig. 10. The scatter in the plot is mostly due to the uncertainty in estimating the slope; for some wind directions the high correlation region is discontinuous (as seen in Figure 8b-ii, 9b-i) due to surface heterogeneity. The advection speeds are similar to the wind speed at 8 m a.g.l. with a decreasing trend in less unstable conditions.

Wilczak and Tillman (1980) also reported that the speeds of surface layer plumes are greater than wind speed at 4 m a.g.l. with a small decreasing trend with stability. As the surface layer becomes less unstable, the strength of buoyant production decreases compared to shear production, resulting in less turbulent mixing. This causes a larger vertical gradient of horizontal wind speed in the upper part of the surface layer and also a smaller effective plume height. The advection speed, i.e. the mean wind speed over the height of the surface layer plume, should be identical to u_s of ST coherent structures. Thus, with increase in the stability of the boundary layer the u_s decreases compared to the wind speed at a sufficiently large altitude (e.g. 8 m a.g.l. in this case). Also as seen in Figs. 2-c, except for 25 June the mixed layer wind speed is similar to the wind speed at 8 m a.g.l. Consequently, one can conclude that u_s is similar to the mixed layer wind speed. This is consistent with Katul et al. (1998) and Renno et al. (2004) who – in the absence of thermal imagery - resorted to more elaborate spectral analysis to sugggest that ST structures are caused by mixed layer turbulence.

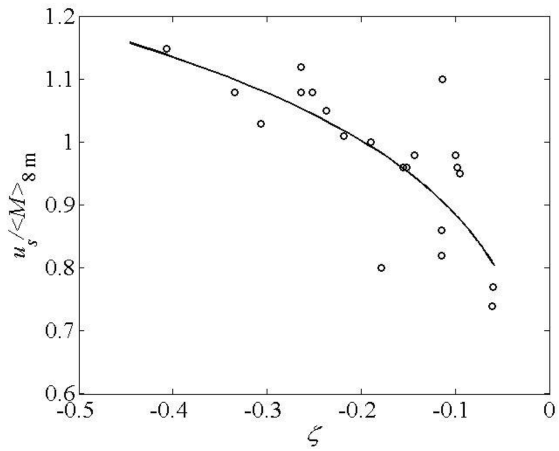


Figure 10. Advection velocity of the ST structures (determined from Fig. 9) versus the 8 m wind speed as a function of ζ. Markers represent the measurements and the solid line represents the fit equation ${u_s}/{\langle M\rangle_{8\,\mathrm{m}}} = 1.34(-\zeta)^{0.18}$ with 57.1% coefficient of determination.

f. Conditional averaging of ejection events

To study the coupling between ST and near surface coherent structures in more detail, conditional averaging was employed. Events are classified as strong ejection events if $w'T_a'_{8m} > 0.5\langle w'T_a'\rangle_{8m}$, *w'* is positive, and the minimum duration of the event is 3 s. Also, if two consecutive events are separated by less than 5 s, they are merged into a single event. Estimated events are then verified by visual inspection of the time series to ensure no false identification. These criteria result in 20 to 30 ejection events per stationary period with time scales ranging from 3 s to 45 s. The events cover around 20 to 25% of each 30 min stationary period, but are responsible for 60 to 70% of the sensible heat flux. Since the duration of each ejection event is different, time was normalized by the individual ejection time scale such that *t* = 0 and 1 indicates the start and end of the ejection event at 8 m a.g.l. respectively.

The ejection event is initiated by surface heating (Fig. 11-i). Since net radiation is nearly constant during the short time frame of the event, the increase in ground heat flux associated with surface heating has to be balanced by decreases in the convective fluxes. Thus before the ejection event, $w'T_a'$ is small. During the ejection event (Fig. 11-i) the warm air rises due to buoyancy, forming a surface layer plume. The majority of the vertical heat flux occurs during the ejection events (Fig. 11-ii) and buoyant production increases compared to shear production (Fig. 11-iii). After the ejection event, a downward flow of cold air occurs as a sweep event. The large convective heat flux during the ejection leads to cooling of the surface and as a result the ground heat flux decreases until the end of the sweep event. Also, note that though AT shows a ramp-like pattern (AT remains almost constant during the sweep, gradually increases during the sweep to ejection transition, attains maximum at the ejection and drops sharply during the ejection to sweep transition), the change in ST is smoother (gradual increase and decrease during sweep to ejection and to sweep events). This might be attributed to the higher thermal inertia of the surface compared to the air, so that small scale variations average out over the surface.

Though AT and ST follow similar trends, there is a time lag; the ST reaches its maximum before the AT and its minimum after the AT consistent with Garai & Kleissl (2011). Also, from Figs. 11-i, it is evident that the plumes are slightly tilted due to wind shear. Since the shear production decreases more rapidly with height than buoyant production, the magnitude of Ri_f increases with height (Figs. 11-iii). Also, the magnitude of Ri_f during the ejection event decreases with increasing stability of the boundary layer. Similar results are obtained for the other stationary periods.

Although the magnitude of G depends on the thermal properties of the ground, the surface heat flux normalized by the mean, $G^* = {}^{G}/_{\langle G \rangle}$, will be independent of ground thermal properties as the ground conduction model is linear. Figs. 11-ii show that the ejection and sweep events cause variations of up to 0.3 times the mean ground heat flux.

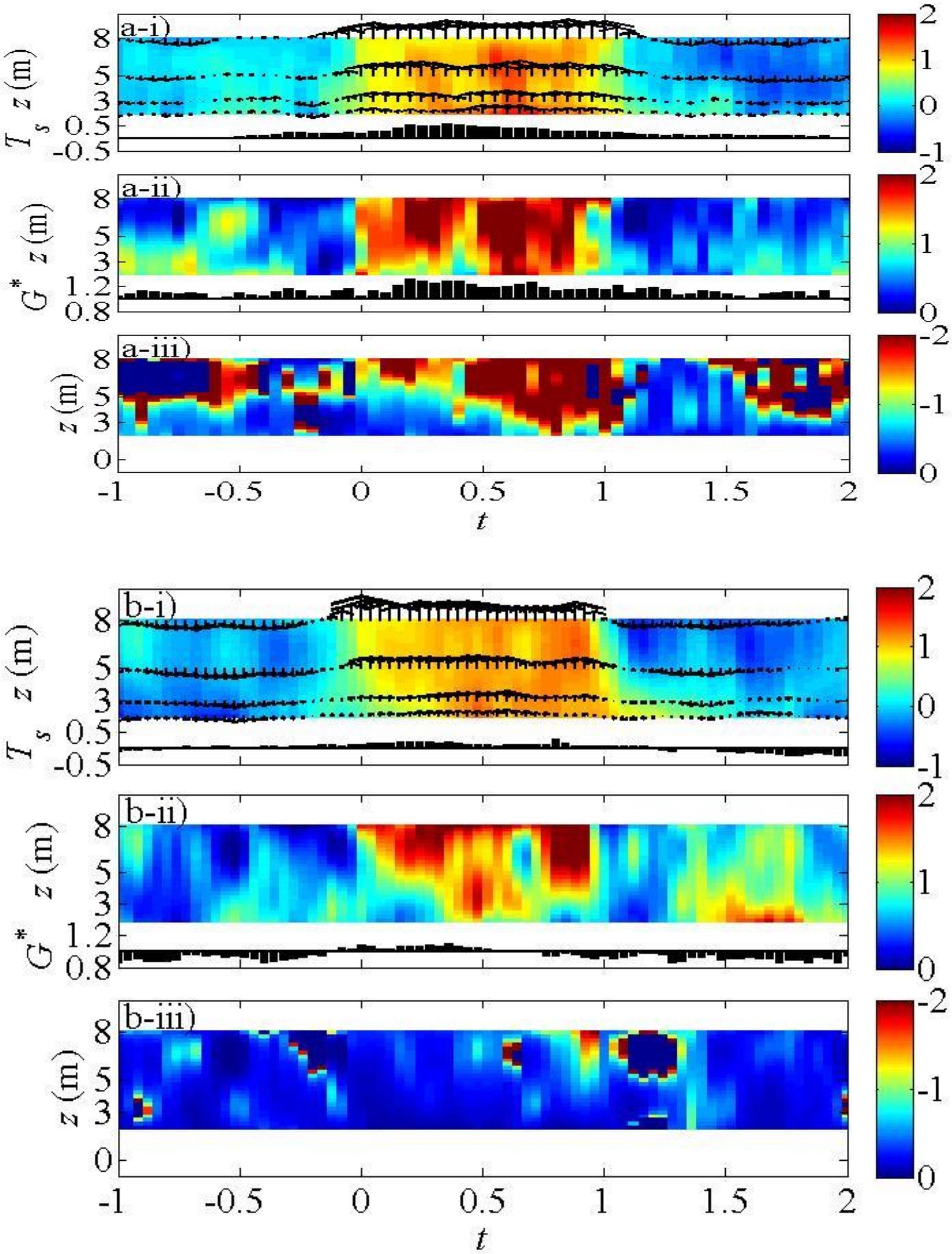


Figure 11. Conditional average of ejection events occurring for L = (a) -10.22 m, and (b) -19.49 m. (i) AT (colour), and ST (bars), both normalized by $-T_*^{SL}$. Vertical velocity vectors are overlayed (largest vector corresponds to 0.4 m s^{-1}). To convert ST to a time series, Taylor's frozen turbulence hypothesis was applied using the advection speed of ST structures (Fig. 9). (ii) $w'T_a'$ normalized by $\langle w'T_a'\rangle_{2m}$ (colour) and modelled ground heat flux normalized by mean ground heat flux (G^*, bars). (iii) Ri_f. The time axes are normalized such that t = 0 and 1 correspond to the start and the end of the ejection event

at 8 m a.g.l., respectively. Note that the ST is not from the footprint of AT, but rather the temperature directly below the AT measurements.

4. Discussion and conclusion

Coupled land-atmosphere heat transfer was examined using lower surface layer eddy covariance measurements and IR surface temperature imagery for a range of unstable conditions in the CBL. The sequential IR images of ST show that temperature patterns in the surface grow, combine with each other and move along the wind. These ST patterns can be interpreted to be the imprints of turbulent coherent structures on the surface in a CBL (Derksen, 1974; Schols et al. 1985; Paw U et al. 1992; Katul et al. 1998; Balick et al. 2003; Ballard et al. 2004; Renno et al. 2004; Vogt, 2008; Christen and Voogt, 2009, 2010; Christen et al. 2011; Garai & Kleissl, 2011). When ST standard deviations are compared with AT standard deviations, they follow a similar trend with respect to stability and the former is smaller than the latter at 8 m a.g.l. The normalized σ_{Ts} gives a similar power law exponent (0.39) compared to surface layer similarity theory (Wyngaard et al., 1971); the coefficient of proportionality differs significantly (for our data, 0.36), but it should depend on the surface thermal property (Tiselj et al., 2001; Balick et al., 2003). Different σ_{Ts} over different surfaces (σ_{Ts} over metallic roofs > lawns > roads > building walls) was also reported by Christen et al. (2012) for an urban measurement site.

Cross-correlating ST and AT, the maximum correlation region aligns with the wind direction. The cross-wind span of the correlation region depends on the standard deviation of the wind direction. The upwind correlation region corresponds well to the scalar footprint formulated from the footprint by Hsieh et al. (2000). The lag associated with the maximum correlation reveals that the upwind ST fluctuations affect the AT fluctuations at the measurement tower and the AT fluctuations at the measurement tower affect the downwind ST fluctuations. This indicates that vertically coherent structures advect smaller and larger temperature fluid downwind and these structures leave a temperature footprint on the surface. The correlation between footprint-averaged ST with AT increases from 2 m to 8 m. All these observations point to the surface temperature fluctuations being caused by turbulent coherent structures in the atmospheric boundary layer.

The mean streamwise size of the ST structures (or rather the turbulent coherent structures that leave an imprint on the surface) decreases with ζ. The *AR* of the structures increases with both u_* and ζ. Wilczak and Tillman (1980) also reported similar values of turbulent structure size and their advection speed in CBL by considering time trace of AT at 4 m a.g.l.. These findings further substantiate that the ST patterns reflect common properties of turbulent coherent structures in the boundary layer. More unstable flows cause more circular and shorter coherent structures while more neutral flows give rise to longer, streaky patterns.

The advection speed of the structures was of the order of wind speed at 8 m a.g.l. and it decreased with stability. The mixed layer wind speed was almost the same as the wind speed at 8 m a.g.l.. Similar results were reported by Christen and Voogt (2009, 2010) and Garai and Kleissl (2011). Katul et al. (1998) and Renno et al. (2004) inferred that high frequency ST fluctuations were caused by mixed layer turbulence.

The ST coherent structures are finally interpreted in the context of the surface renewal (SR) method. While the Lagrangian concept of the SR method cannot be conclusively demonstrated in the Eulerian measurement framework, the observations give rise to the following interaction between coherent structures and the surface. During the sweep event, a cold air parcel descends and the surface cools due to enhanced temperature gradient and heat transfer between surface and air. The cooler surface results in a smaller ground heat flux during this time (Figs. 11-i and ii; $t > 1$ or $-1 < t < -0.5$). As the air parcel remains in contact with the surface it warms gradually, reducing heat transfer between the surface and the air. The ground heat flux increases during this time. Thus, the surface starts to warm (Figs. 11-i and ii; $-0.5 < t < 0$). As the air parcel warms up, it gains buoyancy (Figs. 11-iii). With sufficient buoyancy (and possibly assisted by mixed layer turbulence) the air parcel ascends in an ejection event. During the initial period of the ejection event, the ground heat flux reaches a maximum (Figs. 11-i; $0 < t < 0.5$). As the ejection event continues large heat transfer occurs between the surface and the air (Figs. 11-ii; $0 < t < 0.5$). Afterwards the surface starts to cool and the ground heat flux starts to decrease (Figs. 11-ii; $t > 0.5$).

In Garai & Kleissl (2011), we also analyzed ST structures during different phases of the SR cycle. In this study, with the larger camera field of view and availability of AT at different heights, we have successfully visualized SR events both in the surface layer and on the surface. However, due to the larger camera field of view in this study, a single image contains several SR events at different stages (Fig. 3). Thus the size of the ST structure for each individual SR event is averaged out when spatial correlation within an image is considered (Section 3c). While it cannot be demonstrated in this study, we expect the temporal evolution of the structure size to be similar as found in Garai and Kleissl (2011): during the ejection event there will be a large warm ST structure, during the sweep event there will be a large cold ST structure, at the transition from ejection to sweep there will be small patches of cold ST structures, and at the transition from sweep to ejection there will be small patches of warm ST structures. These ST structures grow, combine with each other and move along the higher altitude wind. Strong sweep events are followed by ejection events and the heat transfer mechanism repeats itself. We observed that the surface reaches maximum temperature before the air and minimum temperature after the air. The majority of heat transport occurs during the ejection event (about 60 to 70% of the total sensible heat flux), which also causes ground heat flux variations (about 30% of the mean ground heat flux) through surface energy budget. Thus the turbulence induced surface temperature variation should be accounted for in numerical models as they cause a considerable amount of surface energy budget anomaly.

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Appendix

The ogive function can be employed to estimate the sufficient averaging period for calculation of turbulent fluxes using the eddy-covariance method. Ogive ($og_{w.X}(f_o)$) is a cumulative integral of the co-spectrum, $Co_{w,X}$, of a variable, *X*, with vertical velocity, *w*, starting with the highest frequency, *f*, $og_{w.X}(f_o) = \int_{\infty}^{f_o} Co_{w,X}(f)df$. Ideally the ogive function increases during the integration from high frequency to small frequency, until reaching a constant value. Hence the period corresponding to the frequency at which the ogive reaches the constant value is considered to be sufficient to capture the largest turbulence scales. To improve the statistical significance and minimize the effect of diurnal cycles, twenty six 30 min segments for each clear days corresponding to 0600 – 1900 UTC were used. It was found that a 5 min averaging period accounts for 90% and 85% of the maximum value of ogive for 2 m and 8 m CSATs respectively for the sensible heat flux (Fig. 12) and the momentum flux (not shown). Thus an averaging period of 5 min was selected.

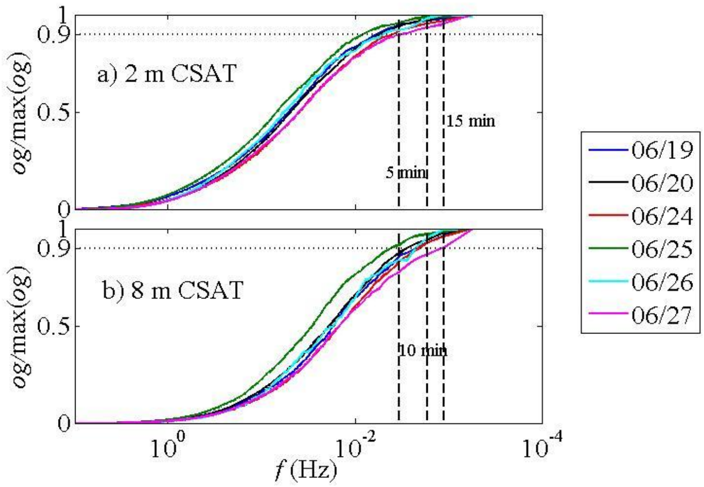

Figure 12. The normalized ogive by its maximum value for heat flux calculation at 2 and 8 m CSAT of all the clear days.

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