Air and Surface Temperature Coupling in the Convective Atmospheric Boundary Layer

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ABSTRACT

In a convective boundary layer, coherent structures were detected through their thermal signature on an artificial turf surface using high-frequency thermal infrared (TIR) imagery and surface layer turbulence measurements. The coherent structures cause surface temperature variations over tens of seconds and spatial scales of tens to a few hundred meters. Evidence of processes similar to those in a renewal event was observed. Spatial and temporal correlation analysis revealed the geometric and velocity information of the structures at the ground footprint of air temperature measurements. The velocity of the coherent structures was consistent with the wind speed at 6.5 m AGL. Practical implications of turbulence-driven surface temperature variability for thermal remote sensing are also discussed.

1. Introduction

In a convective boundary layer (CBL), solar heating causes air near the surface to heat up and ascend through the atmosphere. In laboratory experiments of turbulent free convection over a heated horizontal surface by Townsend (1959), Howard (1966), Kline et al. (1967), and Corino and Brodkey (1969), the temperature fluctuations showed periodic activity, characterized by alternating large fluctuations and periods of quiescence. Flow visualization by Sparrow et al. (1970) reveals that these periodic activities are due to mushroom-like structures of ascending hot fluid. In the CBL, the ascending warm air in the surface layer (ASL) is known as surface layer plumes. Kaimal and Businger (1970), Kaimal et al. (1976), Wilczak and Tillman (1980), and Wilczak and Businger (1983) found that surface layer plumes have diameters and depths on the order of the ASL and an advection velocity that is close to the average wind speed over their depth (Renno et al. 2004). Wind shear causes them to tilt by about 45° in the flow direction (Stull 1997). Above the ASL these plumes become more diffuse and combine to form thermals that have larger length scales, on the order of the atmospheric boundary layer (Caughey and Palmer 1979; Young 1988; Deardorff and Willis 1985). Based on the flow visualizations by Corino and Brodkey (1969) and Sparrow et al. (1970), Liu and Businger (1975) and Brutsaert (1975) proposed analytical models for heat transfer during forced and free convection. They assumed that the eddies responsible for plumelike structures are on the order of the Kolmogorov scale for smooth walls and roughness height for rough walls.

Gao et al. (1989), Paw U et al. (1992), Braaten et al. (1993), and Raupach et al. (1996) studied coherent turbulent structures, known as surface renewal (SR) events, in different canopies. In the SR process (Fig. 1a) a cold air parcel approaches the ground during a sweep. As it stays in contact with the ground, heat is transferred from the ground to the parcel until it has sufficient buoyant force. The heated air parcel then ascends during the ejection event. Thus, the air temperature time series contains saw tooth or ramplike features (Fig. 1b). These ramp patterns were most clearly seen in the middle and upper portion of the canopy. Utilizing the characteristics of these coherent structures, Paw U et al. (1995), Snyder et al. (1996), Spano et al. (1997, 2000), Castellvi et al. (2002), Castellvi (2004), and Castellvi and Snyder (2009) proposed and validated the SR method to estimate surface sensible and latent heat fluxes given the statistics of high-frequency air temperature measurements.

Plumes and thermals such as coherent structures in CBL will then cause high-frequency ground temperature
fluctuation. Paw U et al. (1992), Katul et al. (1998), and Renno et al. (2004) observed such surface temperature fluctuation of around 0.5°C over 2.6-m-high maize crops under unstable conditions, greater than 2°C over a 1-m-high grass-covered forest clearing, and 2–4°C over a desert area, respectively. The fluctuations were attributed to inactive eddy motions (Katul et al. 1998) and convective mixed layer processes (Renno et al. 2004). According to Townsend (1961), turbulent motion in the inner layer of the boundary layer is composed of (i) “active” motion due to the shear near the surface and (ii) “inactive” motion due to turbulence in the outer region. The inactive eddy motion can be detected from the near-surface pressure fluctuations and in the lower wave-number part of the longitudinal velocity spectra (Katul et al. 1996).

Vogt (2008) and Christen and Voogt (2009, 2010) visualized the spatial surface temperature field, respectively over a bare field and in a suburban street canyon, using 1-Hz thermal infrared (TIR) imagery. Heat transport from urban lawns was qualitatively attributed to coherent structures and small-scale turbulence. Balick et al. (2003) studied spatial variation of surface temperature from satellite imagery and modified the Brutsaert–Liu–Businger surface renewal approach to couple surface temperature with turbulent heat flux. From 1-Hz TIR data Kustas et al. (2002) studied the energy budget at a riparian corridor.

While turbulent coherent structures in the convective boundary layer are well understood, their effect on the surface skin temperature is less studied. Our objective is to connect these different research areas by analyzing the spatiotemporal structure of skin temperature fluctuations and their coupling to atmospheric turbulent coherent structures. Ultimately this research could lead to a more fundamental understanding of land–atmosphere interaction and heat transfer at the earth’s surface. In sections 2, 3, and 4 we describe the experimental method, results, and conclusions, respectively.

2. Experiment and data processing

a. Experimental setup

The experiment was conducted over the 115 m × 60 m Torrey Pines High School (TPHS) artificial turf football field (32°57’N, 117°23’W) on 1 May 2010 (Fig. 2). Surface albedo was measured as 0.06 [both for the visually lighter and darker 5-yd (4.57-m) stripes] using a Kipp & Zonen CM6 thermopile albedometer.

TIR images at TPHS were gathered using a FLIR A320 Thermacam operated at 1 Hz 15 m above ground level (AGL). The TIR camera records longwave radiation from 8- to 14-μm wavelength in 240 × 320 pixels and converts them to surface temperature $T_g$ assuming an emissivity of 0.95. The accuracy of $T_g$ is 0.08 K. A coordinate system transformation and interpolation was performed to a bird’s-eye view, resulting in footprints of 48 m × 15 m with uniform resolution of 0.15 m × 0.08 m.

Global horizontal irradiance (GHI) was measured by a Licor 200SZ pyranometer. Turbulence data were measured using a Campbell Scientific Sonic Anemometer–Thermometer (CSAT; measuring velocities $u$, $v$, and $w$ and sonic temperature $T_s$) and one fine wire thermocouple (measuring air temperature $T_a$) at 1.5 m AGL and at 10 Hz. Since $|⟨w⟩|/M < 0.0135$ ($M$ is the mean horizontal wind speed and angle brackets denote averaging), a coordinate system rotation was not necessary. Time-averaged (i.e., persistent) ground surface temperature $⟨T_g⟩$ at 1.5 m AGL was observed and the tripod was placed within the camera footprint such that upwind $⟨T_g⟩$ variations were small. Also, when $⟨T_g⟩$ was subtracted from $T_g(x, y, t)$, visual inspection showed no effect of the spatial heterogeneity on the evolution of $T_g'(x, y, t)$, where the prime denotes fluctuations about the temporal average.

b. Data processing

The ogive test (Foken et al. 2006) revealed that a 5-min averaging period is sufficient for estimating the momentum and heat flux from the eddy covariance method. To ensure that the resulting time series are not affected by changes in meteorological conditions, fluctuations of wind speed, temperature, and ground temperature were calculated by removing the 5-min trends from the data:

\[ \text{TIR camera footprint such that upwind } ⟨T_g⟩ \text{ variations were small. Also, when } ⟨T_g⟩ \text{ was subtracted from } T_g(x, y, t), \text{ visual inspection showed no effect of the spatial heterogeneity on the evolution of } T_g'(x, y, t), \text{ where the prime denotes fluctuations about the temporal average.} \]
\[ X'(t) = X(t) - (X)_{5\text{min}} + a_{X,5\text{min}} t, \tag{1} \]

where \(a_{X,5\text{min}}\) is the linear time dependence coefficient of parameter \(X\). For comparing 10-Hz turbulence data with 1-Hz \(T_g\) data, we used a box filter of size 1 s centered at the time stamp of \(T_g\). The thermocouple air temperature was used to calculate the kinematic vertical turbulent flux of sensible heat \(h_T\). For the arid artificial turf surfaces air temperature fluctuations are close to virtual temperature fluctuations. The heat flux footprint was estimated using the model proposed by Hsieh et al. (2000) in the streamwise direction. A cross-stream width of 3 m was assumed (see Fig. 5), which encompasses the region for which the footprint function is greater than 70% of its maximum for the conditions analyzed in section 3. Then the weighted average of \(T_g\) over the flux footprint was computed.

3. Results

Clear skies with southwesterly winds prevailed at TPHS (Fig. 3). The sensible heat flux was 200–400 W m\(^{-2}\), \((T_g)\) was 45°–55°C, horizontal wind speed was 1.5–3 m s\(^{-1}\), and \((T_a)\) was about 18°C. Nearly constant Obukhov length \((L = -5.66\text{ m})\) and less wind direction variability (standard deviation of the wind direction less than 20°, not shown) motivated the selection of the period 1130–1200 Pacific standard time (PST) for further analysis. During this time period, the friction velocity \(u_*\) was 0.26 m s\(^{-1}\) and nondimensional shear \((dM/dz)(z/u_*)\) was 1.65. With the camera facing west at a beam angle of 18.8° from horizontal, solar noon at 1146 PST, and solar zenith angles of 18.1° or less, during this time period the grass blade shadows are small and their motion has only a small effect on changes in measured surface temperature. Assuming a typical inversion height \(z_i\) of 500 m for the sea-breeze meteorology in coastal California, the convective velocity scale \(w_*\), temperature scale \(T_*\), time scale \(t_*\), and flux Richardson number \(Ri\) were respectively 1.62 m s\(^{-1}\), 0.98 K, 309 s, and −0.46.

The statistics of velocity and temperature fluctuations (standard deviation \(\sigma\), skewness, kurtosis) are reported in Table 1. Figures 4a–c depict a typical 5-min time series of ground and air temperature, heat flux, and \((u', w')\) velocity. Ejection events (updrafts with positive \(w'\)) occur less frequently but are associated with large heat fluxes than sweep events (downdrafts with negative \(w'\)). To study the lower-frequency evolution of the temperature fluctuations we used wavelet analysis (Hudgins et al. 1993). For a time series \(f\), its wavelet function \(W_f\)
can be calculated by $W_f(s,t) = \int f(t) \psi_s(t - \tau) d\tau$, where $s$, $\tau$, and $\psi_s$ are respectively scale, time, and mother wavelet function (Morlet wavelet, in this case). Thus, wavelet analysis yields not only the spectral measure of variance, but also the time instant when it appears. We can use wavelets to detect surface renewal events and analyze wind speeds and temperatures during those events.

Figures 4d and 4e show the wavelet scalogram of the air and ground temperature fluctuation. There is a similarity between the $T'_{ag}$ and $T'_{ag}$ scalogram for scales of 60 s and higher and the $T'_{ag}$ time series lags $T'_{ag}$ by about 20 s. Consistent with the time series plot of $T'_{ag}$ and $T'_{ag}$ (Fig. 4a) and energy spectra (not shown), smaller-scale $T'_{ag}$ fluctuations ($<20$ s) have more energy than $T'_{ag}$. This is due to the fact that the ground has a larger thermal mass than air and also to the spatial averaging over the footprint. Consequently, the ground temperature signature of small eddies falls below the 0.08-K noise level of the TIR camera. The 1-Hz TIR data acquisition frequency (the highest possible with this TIR camera model) was sufficient to resolve the majority of $T'_{ag}$ fluctuations.

One would expect a correlation between $T'_{ag}$ and $T'_{ag}$ within the footprint of the CSAT (as seen in Fig. 4a). The temperature of an air parcel is affected by the temperature within its upwind ground footprint. Thus, the correlation between them should be a maximum when the $T'_{ag}$ time series is lagged by the time it takes for air parcels to be advected from the footprint. On the other hand, as air moves downstream it will affect the downstream ground temperature, causing high correlation with positive lag. Figure 5 shows the maximum correlation and corresponding lag between $T'_{ag}$ and $T'_{ag}$, where a negative lag means that $T'_{ag}$ preceded $T'_{ag}$. The maximum correlation region aligns with the mean wind direction. There is high correlation at both upstream and downstream regions that extends up to 5–10 m in the streamwise direction, with negative lag upstream and positive lag downstream. While this is an expected result, this is the first time that this could be shown explicitly with spatial surface temperature data.

Figure 6 shows only the upstream correlation between $T'_{ag}$ and $T'_{ag}$. The air temperature measurements are conducted at the coordinate origin (0-s lag and 0-m distance). Upwind (negative distance) the lag with

**FIG. 3.** Time series of the 5-min averaged meteorological conditions: (a) air and ground temperature (averaged over the TIR image), (b) wind speed $M$, (c) global horizontal irradiance (GHI) and sensible heat flux $H$, and (d) Obukhov length $L$, for the experiment at TPHS on 1 May 2010. The section between two vertical dotted lines represents the relatively stationary period considered for further analysis.

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<th>Table 1. Standard deviation, skewness, and kurtosis of the velocity components, air temperature, and ground temperature fluctuations during 1130–1200 PST.</th>
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maximum correlation becomes negative. Consequently, this graph is a two-dimensional depiction of correlation value (Fig. 5a) and lag (Fig. 5b) along a line upwind of the $T_g$ measurements. The slope of the line of maximum correlation indicates the velocity of the coherent structures. From the horizontal and vertical separation between a ground pixel and the $T_g$ sensor, the horizontal advection and vertical dispersion velocity of the coherent structures can be estimated, respectively. The estimated horizontal velocity is 3.30 m s$^{-1}$, which is greater than the mean wind speed at 1.5 m AGL and the vertical velocity is 0.48 m s$^{-1}$, which is close to standard deviation of $w$ (Table 1). The upwind maximum correlation region also is qualitatively consistent with the flux footprint function of Hsieh et al. (2000).

We now take further advantage of the spatial information provided by TIR camera to explore the manifestation of a renewal event. A sequence of snapshots of $T_g(x,y)$ during a renewal event is shown in the top row of Fig. 7 for 1149:24–1150:54 PST (from 144 to 234 s in Fig. 4). Initially $T_g$ is negative over the footprint (Fig. 7a), which can be attributed to a sweep event, when cold air comes in contact with ground (A in Fig. 1). Shortly thereafter, several small hot spots appear (Fig. 7b). These hot spots grow, combine, and move in the wind direction (B in Fig. 1). At the subsequent time $T_g$ in the entire image becomes positive (Fig. 7c) indicating an ejection event (C in Fig. 1). As the heated air rises from the ground because of its buoyancy, the ground starts to cool (Fig. 7d; D in Fig. 1) again.

To study these spatial structures we employ principal orthogonal decomposition (POD; Pope 2003). Large structures are reconstructed using the 10 most energetic POD modes and small structures are constructed using the residual nodes (Fig. 7, middle and bottom panels). We caution that since the size of the structures exceeds the size of the TIR camera image, the structures depicted here are not the largest structures. When the ground is either hot or cold (Figs. 7a,c; i.e., during sweep and ejection), the large structures are larger compared to the time when ground is heating up or cooling down (Figs. 7b,d). Following the model of coherent eddies by Williams and Hacker (1992) and Vogt (2008), hot or cold ground (Figs. 7a,c) can be attributed to a transition between two roll vortices near the ground leading to large updrafts or downdrafts. The ground heating up or cooling down (Figs. 7b,d) can be attributed to a roll vortex being centered over the site, leading to sweeping away of small eddies. On the other hand, the residual small structures do not depend on the phase of the

![Fig. 4. Time series of (a) air and ground temperature fluctuations (averaged over footprint), (b) kinematic heat flux, and (c) $u-w$ velocity vector, and scaled wavelet scalogram of (d) air and (e) ground temperature fluctuations for 1147–1152 PST.](image-url)
renewal event. Also, the orientation of the large structures is more aligned with the wind direction compared to the residual small structures (Fig. 8).

Our analysis has shown that the dimensions of the surface temperature scales are larger than the TIR camera image (Figs. 7a,c) and their temporal scale is several advection time scales through the image (Fig. 4). Ideally the TIR camera footprint should be greater than the large scales, but even with our wide-angle lens this would require flying the camera on a stabilized balloon at several hundred meters in altitude. To illustrate the spatiotemporal evolution of the structures, we draw a line through the image in streamwise direction and plot the time evolution of $T_g^9$ along this line for 1147–1152 PST in Fig. 9a. Most large events indeed last tens of seconds and are larger than 20 m in scale. Based on Fig. 9a, but considering all lines aligned in the streamwise direction, Fig. 9b provides the mean of the correlation statistics across space and time. The advective nature of the structures can be seen from the upward slope of the hot and cold “stripes” of $T_g^9$ in Fig. 9a and the downward slope of the spatiotemporal correlation profile in Fig. 9b. The estimated horizontal velocity from the slope of spatiotemporal correlation profile for the structures is 3.18 m s$^{-1}$, which is also close to the estimated horizontal velocity from the ground–air correlation (Fig. 6). Also, the high correlation region in Fig. 9b indicates both the temporal and spatial extent of a structure in the downwind direction.

**Fig. 5.** Spatial dependence of (a) maximum correlation and (b) corresponding time lag (s) between air and ground temperature for 1130–1200 PST. The black vertical bar marks the location of the tripod and the black arrow represents the mean wind direction. The white region in Fig. 5b indicates a ground–air temperature correlation of less than 0.2.

**Fig. 6.** Correlation map between air temperature and upwind ground temperature at different distances (x axis) and time lags. The horizontal white line represents zero lag.
4. Conclusions

In this proof-of-concept study we evaluate the ground and air temperature interaction for the convective atmospheric boundary layer using TIR imagery. With only data from 1 day presented, the analysis is not exhaustive and more extensive studies on the topic are needed, but practical issues (since the thermal camera is expensive and not waterproof it cannot be left unattended) and lack of funding make long-term studies difficult. Most existing eddy covariance sites are not suitable to conduct the experiment since short vegetation is required. In the absence of vegetation (e.g., over a parking lot), the thermal admittance is too small and $T_g$ cannot be detected (not shown). If the vegetation is too high, "honami" or ocean wave–like motion of crops will occur and the resulting shading and varying solar incidence angle pattern complicate the analysis (Finnigan 2010). The ideal site for this experiment would be a dry (large buoyancy), flat, and homogeneous surface (no roughness or inhomogeneity effects) with small vegetation (eliminating honami effects of tall vegetation yet preserving large thermal admittance of vegetation versus sand or asphalt) and a high viewpoint for camera. Our site fulfilled all criteria except for the large-scale homogeneity. Nearby berms and buildings may have led to shedding of eddies, but the low wind speed reduced the effect of eddies shed by surrounding building. Surface temperature spectra did not show an increase in energy near the expected shedding frequency of eddies from nearby obstacles. While other researchers have examined $T_g$ variability, our study is the first to provide a thorough quantitative spatial analysis of surface–atmosphere exchange using TIR imagery.

The speed of the coherent structures was 1.5 times the wind speed at 1.5 m AGL and consistent with a velocity at 6.5 m AGL (estimated from the stability corrected log profile). Christen and Voogt (2010) reported the speed of these coherent structures to be twice the wind speed at about 0.5 m AGL. This difference in ratio between the speed of the coherent structure and wind may be due to the fact Christen and Voogt (2010) gathered their measurement closer to the surface and inside a street canyon, compared to our open field. Katul et al. (1998) found that $T_g$ fluctuations are driven by inactive eddy motion, which scaled as mixed layer turbulence. Our wavelet analysis showed that only large coherent structures leave a $T_g$ signature and these structures (time scale $> 60$ s) are responsible for the majority of the sensible heat flux. Also air temperature at 1.5 m
AGL was correlated to upwind and downwind $T_g$ in a region of width of about 5 m (about 3 times the measurement height).

In a convective atmospheric boundary layer, mixed layer roll vortices are the large-scale eddies responsible for transport of momentum, heat, and mass. While we can only observe the manifestations of atmospheric turbulence on surface temperature, we believe that the observed patterns are consistent with the following concepts. The downward-flowing part of this mixed layer roll vortex or 3D cell will cause cold air to approach the ground during a sweep event. This cold air in contact with the warm ground will cause a large heat flux from ground to the air, causing large portions of the TIR imagery to cool. With time the air heats up, causing heating up of the ground. This phenomenon manifests itself by small hot patches. As the air and ground heat up, the warm air will result in an updraft due to its buoyancy, which represents the thermal or upward-flowing part of mixed layer roll vortices or 3D cells. After the updraft, the surrounding cold air will approach the ground and the cycle repeats. As these roll vortices or 3D cells are advected by the wind, the ground temperature footprint of these structures moves in the wind direction. Thus turbulence in the unstable atmospheric boundary layer induces coherent patterns of $T_g$ fluctuations that can be visualized through TIR imagery. An additional experiment was conducted for stable conditions at the 285 m × 150 m irrigated grass field (RIMAC) at the University of California, San Diego (32°53′N, 117°14′W), on 10 August 2010. At RIMAC, the surface temperature fluctuation signal consisted only of white noise, presumably because surface temperature variations were below the noise level of the TIR camera. This finding is consistent with the fact that coherent structures and air temperature variances are smaller in stable conditions.

We observed within-image temporally averaged standard deviations of 0.7 K, which is 0.7 times the convective temperature scale $T_g$, consistent with the value measured for a high-resolution satellite image by Balick et al. (2003). The temporal standard deviation of $T_g$ (Table 1) is also comparable with the studies carried out by Katul et al. (1998) and Renno et al. (2004). The $T_g$ fluctuations driven by atmospheric turbulence have practical implications for remote sensing, for instance of land mine signatures or evapotranspiration (ET) for irrigation management. Hydrologic energy balance models [e.g., the Surface Energy Balance Algorithm for Land (SEBAL) by Bastiaanssen et al. 1998a,b] derive the sensible heat flux (and ET) through the surface energy balance from spatial differences in surface and air temperature. The large coherent structures can introduce physical “noise” in ET estimates especially if single-image satellite or aerial TIR imagery at high spatial resolution is used.

![Diagram](http://journals.ametsoc.org/jas/article-pdf/68/12/2945/3529036/jas-d-11-057_1.pdf)
Acknowledgments. We would like to express our gratitude to Greg Snelling at RIMAC field of UCSD and Mr. Garry W. Thornton at Torrey Pines High School for providing access to their fields. Billy Hayes, Anders Nottrott, and Khristina Rae Hernandez provided field assistance. We are indebted to Jamie Voogt (University of Western Ontario) for discussing the experimental strategy. This study was funded by NSF CAREER and NASA New Investigator Program awards.

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FIG. 9. (a) Temporal evolution of $T'_{9}$ along a line through the image oriented in the streamwise direction. (b) Spatiotemporal correlation of $T'_{9}$ at a point to points upstream in the streamwise direction at distances of 0–20 m for different time lags.