Exchange Processes at the Land Surface for a Range of Space and Time Scales
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A comparison between measured local scale suburban and areally-averaged urban heat and water vapour fluxes

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Abstract Sensible and latent heat fluxes are estimated from temperature and humidity profiles measured in the convective boundary layer (CBL) above Sacramento, California during late Summer, 1991. The CBL integrates over spatial scales of *ca* 100 km^2, thus these profiles represent the urban boundary layer and the derived sensible and latent heat fluxes represent areal averages from the urban surface. The observed temperature structure is well represented by a simple slab model which, when integrated, yields an equation for estimating time and space averaged scalar fluxes, accounting for entrainment. The estimates of urban scale sensible heat fluxes compare well with simultaneous local scale (suburban) fluxes directly measured in a suburb of Sacramento. These measurements are thus representative of the urban scale input of heat into the urban boundary layer. The complexity of the upper-level humidity profiles leads to poorer estimates of latent heat fluxes.

INTRODUCTION

In the last 10-15 years a range of studies have used simple CBL models to predict regional scale evaporation (e.g. Brutsaert and Mawdsley, 1976; McNaughton and Spriggs, 1986; Cleugh, 1991). CBL scalar concentrations have also been used to infer cumulative, regional scale scalar fluxes (e.g. H_2O: Munley and Hipps, 1990; CO_2: Raupach, *pers comm*). Raupach (1991) showed that the CBL has length scales of adjustment of 1-10 km such that scalar concentrations represent areal averages up to 100 km^2, illustrating the validity of using the CBL to infer regional scale surface fluxes. Simple CBL models thus offer a useful method for integrating across spatial scales *viz* from local scale to regional and global scales. Most studies using the CBL to infer regional scale fluxes have focussed on agricultural landscapes (e.g. crops, pasture or prairie). The *urban* environment has received far less study despite the impact of urban land use on local and regional scale climates.

A picture of energy partitioning at the urban surface-atmosphere interface (Oke, 1988, Schmid *et al*, 1991) has emerged from observational studies mostly conducted in suburban land use with upwind source areas of 2-3 km. Whether these fluxes represent the much larger urban area (up to *ca* 100 km^2) is addressed in this paper. The land use units (*viz* residential, commercial etc.) comprising a city represent the largest spatial scale (L) of heterogeneity. This surface heterogeneity is considered to be microscale (Shuttleworth, 1988; Raupach, 1991) if $L << X$ where X is the length scale of CBL adjustment based on horizontal and convective velocities and CBL depth. Urban boundary layer (UBL) temperature and humidity profiles will then represent an areal average of all the underlying surfaces. Local scale *suburban* flux measurements can be considered to represent urban scale energy fluxes if they agree with UBL derived energy fluxes. Such agreement will also mean that either the heterogeneity in the urban environment is microscale, or that suburban land use is the dominant influence on the UBL. These ideas are examined through a comparison of local scale direct measurements of sensible and latent heat fluxes with estimates derived from radiosonde ascents.

CBL MODEL EQUATIONS

Spatially and temporally integrated fluxes are derived from the simple slab model of the CBL (Fig. 1). Observations reveal that this simplification is valid under clear sky, typically anticyclonic synoptic forcing. The CBL comprises a thin surface layer with large scalar gradients lying beneath a well-mixed layer where convective turbulence and strong mixing reduce these gradients so that they are height-independent. Above the mixed layer is the upper atmosphere whose properties are determined by synoptic processes. The upper limit of the mixed layer, z_i, is usually marked by a potential temperature inversion with gradient γ_Θ ($d\Theta/dz$) while the specific humidity gradient (γ_q) is lapse in the upper atmosphere. The interfacial zone between the mixed layer and the upper atmosphere is parameterized as a step change ($\Delta\Theta$,Δq) in the zero order slab model. The mixed layer grows from sunrise

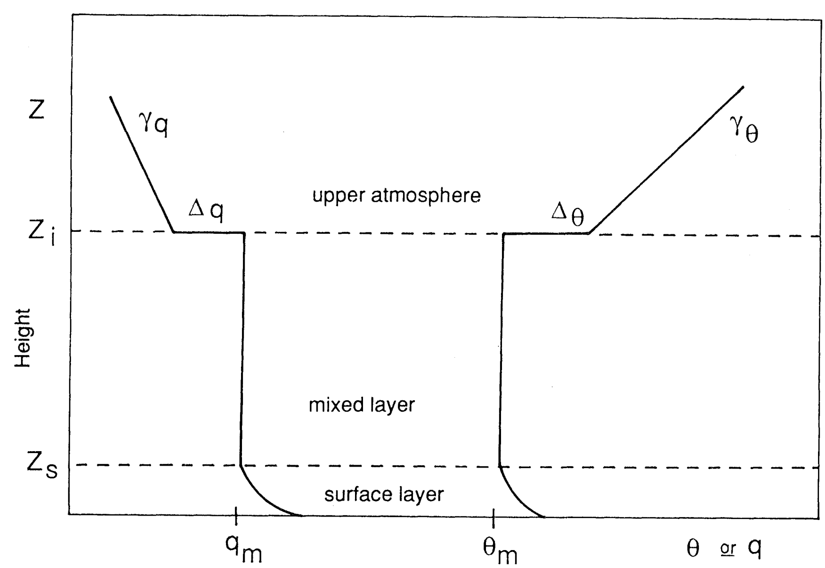


Fig. 1 A schematic showing the "slab" model representation of the CBL. See text for explanation of symbols.

with sensible heating of the surface leading to encroachment into the nocturnal inversion. Plume bombardment at the base of the capping inversion begins to entrain warm, dry air from aloft yielding a discontinuity ('jump') in the vertical profiles of temperature and humidity. The terms $\Delta\Theta$ and Δq are a simple parameterization of this entrainment process.

This basic conceptual model treats the mixed layer as a "slab" of atmosphere which is transparent to radiation with scalar budgets that change through time as a result of vertical divergence or convergence in scalar fluxes. The CBL budget for a scalar with concentration, S, surface kinematic flux, F_s and step change ΔS can be written as:

$$\frac{dS}{dt} = \frac{F_s + \Delta S \frac{dz_i}{dt}}{z_i} \quad (1)$$

This can be rearranged (see e.g. McNaughton and Spriggs, 1986 or Raupach, 1991):

$$\frac{d(z_i \Delta S)}{dt} = \gamma_s z_i \frac{dz_i}{dt} - \int_{t_1}^{t_2} F_s(dt) \quad (2)$$

If γ_s remains constant from t_1 to t_2, (1) can be integrated and rearranged to yield the following expression for the cumulative flux of S from t_1 to t_2:

$$\int_{t_1}^{t_2} F_s(dt) = \frac{\gamma_s}{2}[z_i(t_2)^2 - z_i(t_1)^2)] - [(z_i \Delta S(t_2)) - (z_i \Delta S(t_1))] \quad (3)$$

Equation 3 provides a method for obtaining the integrated, or cumulative, flux of a scalar from the surface into the mixed layer from a time series of radiosonde ascents.

METHODS

The surface layer flux measurements and radiosonde ascents were obtained during an urban energy balance measurement study in Sacramento, California in late August 1991. Site details are presented in Grimmond *et al* (this volume) together with a summary of the prevailing synoptic regime.

Surface Energy Balance Measurements

Local scale radiation and turbulent fluxes were measured directly at a height of 29 m in the suburb of Carmichael. Continuous 15-min averages of all fluxes were measured over an 11-day period (Year/Day 91/231-91/241). The turbulent fluxes of heat (Q_H) and water vapour (Q_E) were determined via the eddy correlation approach, using a one-dimensional sonic anemometer/thermocouple system and a krypton hygrometer which were sampled at 5 Hz and averaged over 15 min. All-wave net radiation (Q^*) was measured (1 s sampling rate) with a Swissteco miniature MK II net pyrradiometer. A 21X micrologger sampled and processed all sensor signals. See Grimmond *et al* (this volume) for further energy balance measurement details.

UBL Profiles

Free flying radiosondes (AIR "airsondes"), attached to helium-filled meteorological balloons, were released and tracked at varying intervals on each day (Table 1). The pressure, wet and dry bulb temperatures were sampled at 10 s intervals. These were converted to potential temperature and mixing ratio in real-time by the ground- based receiver. The balloon elevation and azimuth angles were also recorded at 10 s intervals enabling wind speed and direction to be computed on-line. An aspirated psychrometer was used to calibrate the airsonde sensors prior to release.

Table 1 Release times for all UBL radiosonde ascents.

YD/Flight No.	Time of UBL Profile (PDT)	Reference No. for Energy Fluxes
234/1	07.00	
234/2	13.15	234(1)
235/1	07.20	
235/2	15.30	235(1)
236/1	06.50	
236/2	11.50	236(1)
236/3	16.50	236(2)
238/1	06.45	
238/2	11.40	238(1)
238/3	15.15	238(2)
239/1	06.45	
239/2	09.20	239(1)
239/3	14.50	239(2)
240/1	06.45	
240/2	08.10	240(1)
240/3	09.45	240(2)
240/4	11.45	240(3)
240/5	15.15	240(4)
240/6	17.15	240(5)

Analysis and Processing Details

All energy balance data were calibrated, corrected and then averaged to yield hourly fluxes. These were linearly interpolated to 5-min fluxes to allow the computation of appropriately weighted, cumulative Q_E and Q_H fluxes. This was necessary as radiosonde release times (t_n) did not always coincide with the hourly flux intervals (e.g. t_1 = 1010 PDT and t_2 = 1320 PDT).

Values of γ_Θ were determined using linear regression analysis of the upper atmosphere potential temperature profiles. While this is valid for γ_Θ, the

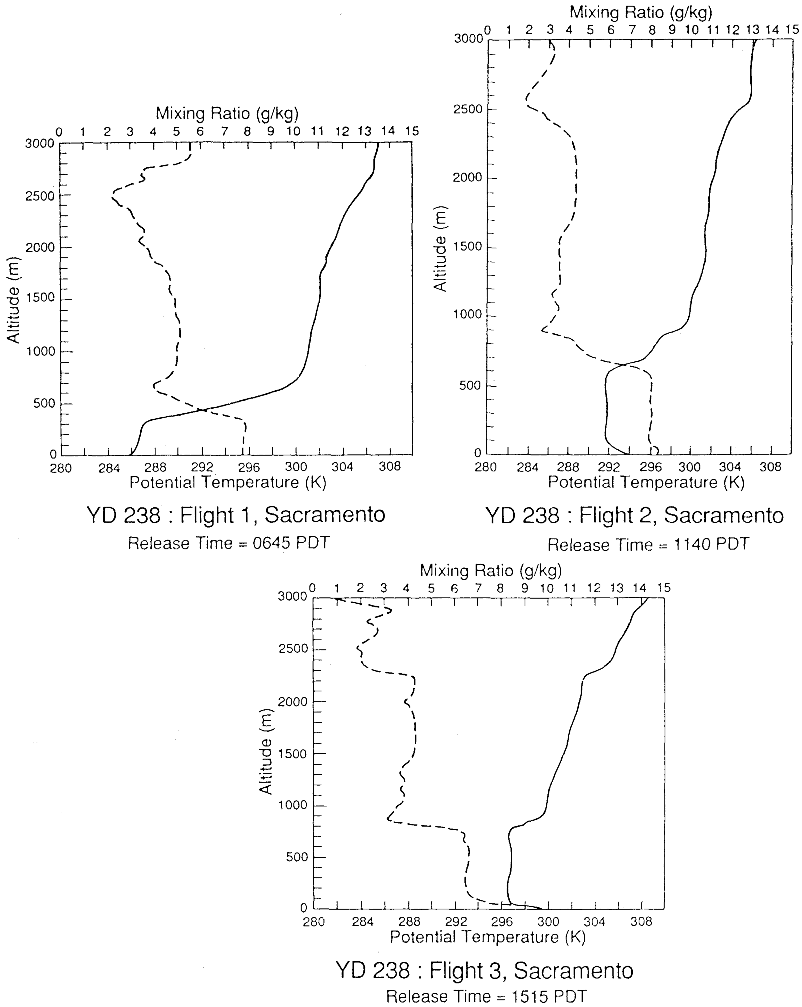


Fig. 2 **A typical diurnal sequence of temperature and humidity profiles for the convectively-dominated urban boundary layer over Sacramento, California. Solid lines and dashed lines represent potential temperature and mixing ratio profiles respectively.**

complexity of the humidity profiles (Fig. 2) prevented such an approach for γ_q. Q_E is estimated by setting γ_q to zero whenever γ_q could not be determined. For the calculations mixing ratio, r, was used instead of q which is valid given that differences between r and q are very small (less than 1%). Values for $\Delta\Theta$ and Δr were derived from the graphed profiles. The method given by Driedonks (1982) was used to determine z_i, $\Delta\Theta$ and Δr on mornings when no clear step was apparent.

RESULTS AND DISCUSSION

A typical diurnal sequence of profiles is shown in Fig. 2. Clearly the potential temperature structure matches the slab model of a CBL very well. This was evident in all the temperature profiles and means that such a model is appropriate for use in the UBL during convective conditions. All profiles showed constant γ_Θ over the day, except on YD 235 when γ_Θ decreased from 0.01°C m^{-1} (0700 PDT) to 0.0046°C m^{-1} (1500 PDT). The remaining 13 estimates of Q_H are plotted both as a time series and scatterplot in Fig. 3. The agreement is surprisingly good (r^2=0.82,

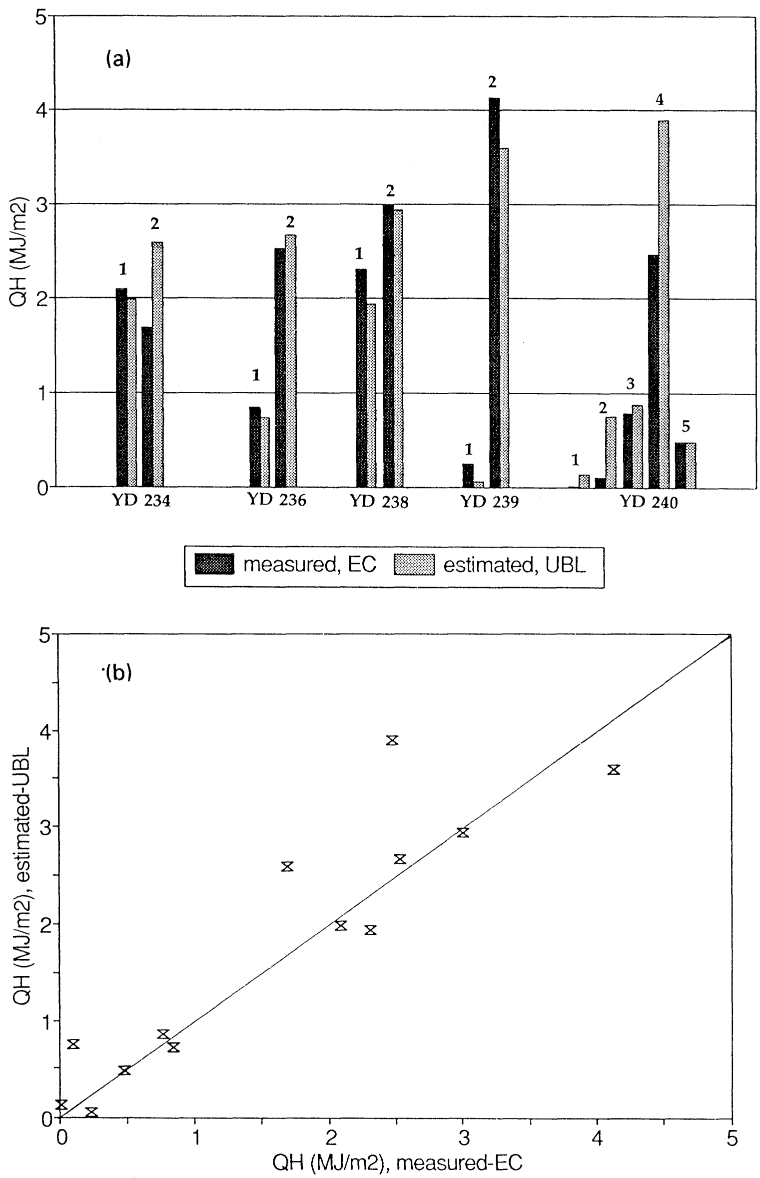


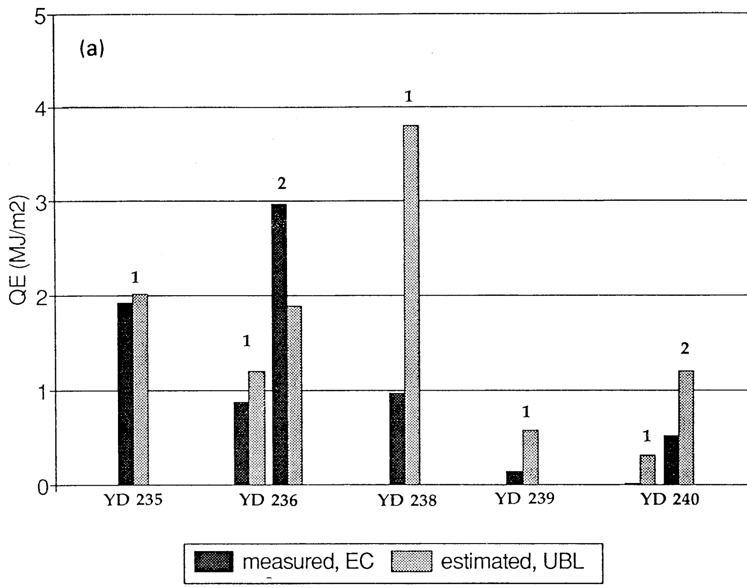
Fig. 3 (a) Time series of estimated (UBL) and measured (EC) cumulative sensible heat fluxes (MJ m^{-2}). (b) Scatterplot of estimated (UBL) and measured (EC) cumulative sensible heat fluxes (MJ m^{-2}). Numbers refer to the reference no. in Table 1.

slope of line of best fit=1.04, mean average error=0.15 MJ m^{-2} or 9%), considering the simple modelling approach and the different spatial scales represented by the direct measurements and UBL estimates. Slight (0.2 MJ m^{-2} *ca* 20-30 W m^{-2}) differences occur for two early morning estimates, *viz* $Q_H(1)$ on YD 239 and 240. Larger discrepancies are found on YD 240 ($Q_H(2)$ and $Q_H(4)$) of 100 W m^{-2} (0.8 and 1.5 MJ m^{-2} respectively). Early morning differences may arise from differing "source areas". This would mean that the tower-based measurements are influenced by the evaporation of dewfall from the surrounding vegetation, whereas the UBL temperature may be influenced by the input of heat from the rougher, built-up urban surface. The profiles used to derive $Q_H(4)$ showed no clear $\Delta\Theta$ which may lead to flux differences. Also, as detailed in Grimmond *et al* (this volume), a cold front passed through the Sacramento area on YD 240. This shift in synoptic forcing may also have contributed to modelling discrepancies.

There is much poorer agreement (Fig. 4) between measured and estimated latent heat fluxes. Fig. 4 includes fewer data points because temporal changes in the upper atmosphere humidity structure indicated large-scale advection. The computed latent heat fluxes were obviously incorrect and thus discarded. The mean average error between the remaining measured and estimated latent heat fluxes is 0.5 MJ m^{-2} or *ca* 50% of the mean flux, where n=7.

CONCLUSION

The slab model can be used with measured Θ and q profiles to estimate urban scale sensible heat fluxes. The agreement between these fluxes and suburban surface-layer measurements is remarkably good considering the large variation in sensible heat fluxes observed over other land uses in the region. Grimmond *et al* (this volume) find a large range in Bowen ratio between unirrigated, tall grass (>10) and irrigated, short grass (0.25) which comprises the land use surrounding the city of Sacramento. The good agreement implies that the surface heterogeneity in the urban environment is being adequately sampled, even at this local scale. It is also possible that suburban land-use so dominates the typical urban landscape in North American cities that the convective UBL structure and properties are determined mostly by this land-use. This may be especially so in this study where the predominantly westerly airflow during the study period yielded *ca* 20 km of urban and suburban land-use upwind of the Carmichael site. Thus tower-based measurements in the suburban surface layer may provide reasonable estimates of urban scale (areally-averaged) heat fluxes because the surface heterogeneity is mostly microscale. However further work is needed to identify the spatial scales of variability in the urban environment and to compare averaging areas for the UBL and surface layer. The slab model is not appropriate for accurately estimating urban scale latent heat fluxes for this location, although some reasonable estimates can be obtained by setting γ_q to zero. The method shows greatest sensitivity to estimates of z_i. On this basis, tethered sondes or acoustic sounders may provide better input data to the slab model. Determining z_i from radiosonde profiles *can* yield large errors although such errors are small in this study as z_i was clearly evident in all temperature *and* humidity profiles.



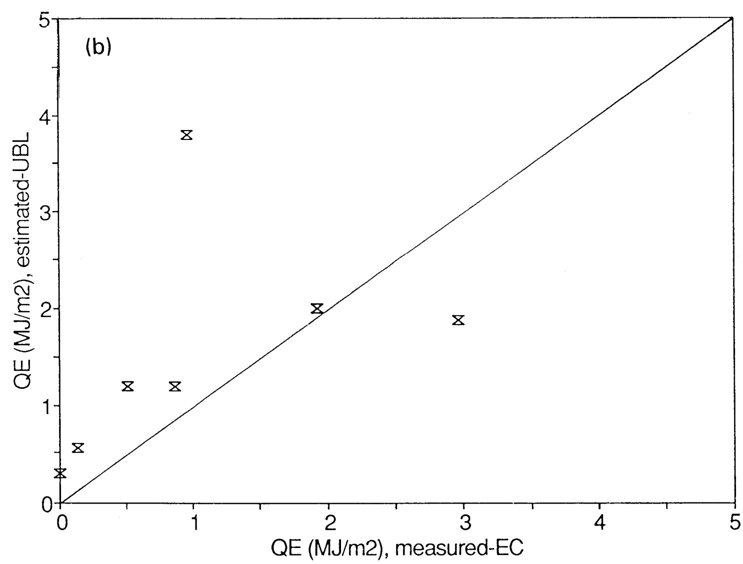


Fig. 4 (a) Time series of estimated (UBL) and measured (EC) cumulative latent heat fluxes (MJ m^{-2}). (b) Scatterplot of estimated (UBL) and measured (EC) cumulative latent heat fluxes (MJ m^{-2}). Numbers refer to the reference no. as explained in Table 1.

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