7.1 SENSITIVITY OF SURFACE-ATMOSPHERE ENERGY EXCHANGES WITHIN URBAN AREAS DERIVED FROM SIMULATIONS

Sarah M. Roberts[1,*] , T. R. Oke[1], A. Lemonsu[2], C. S. B. Grimmond[3], and P. Jackson[1]
[1] University of British Columbia, Vancouver, B.C., Canada; [2] Centre National de Recherches Météorologique, Météo-France, Toulouse, France; [3] Indiana University, Bloomington, IN

1. INTRODUCTION

Understanding the nature of energy partitioning at the surface of cities is prerequisite to gaining proper insight and the ability to model their climatic environment. Of particular relevance in the urban setting is the surface-atmosphere exchange of sensible heat. The combined conductive-convective exchange of turbulent sensible heat flux (Q_H) and net storage heat flux (ΔQ_S) has been shown to account for over 90% of the daytime net radiation at highly urbanized sites. This sharing depends on surface structure, materials and the degree of surface-atmosphere coupling. Understanding sensible heat exchange is essential in many applications; for example, to assess building climates, and to model evapo-transpiration, the urban heat island, and boundary layer growth.

Observational studies, while providing general awareness of urban surface-atmosphere energetic interactions, are often limited in their applicability to other urban sites and/or processes. Numerical models designed to simulate urban climates help overcome the limitations imposed by observations. One such model, the Town Energy Balance (TEB) model of Masson (2000) is implemented here to conduct further analyses to better understand the primary criteria affecting local-scale urban surface-atmosphere energy exchanges. Analyses are performed for a site in Marseille, France.

2. METHODS

2.1 *The Site*

Marseille is situated on the Mediterranean coast in the French region of Provence. The city contains a densely built-up center with very little vegetation, constituting about 16% of plan area (Figure 1). Buildings are the highest roughness elements within the study area and are, on average, approximately 16 m in height. The district comprises primarily 19th century massive limestone and granite administrative, residential and commercial buildings with clay tile or pebble-topped roofs. Streets and sidewalks are asphalt and concrete pavement, respectively, and urban canyons are approximately 7-10 m across. This locale provides an ideal environment for this study,


Figure 1 View from the southwest of the city center of Marseille, depicting the densely built-up urban environment of uniform building heights and little greenspace.

because it has a warm, dry climate (hence sensible heat dominates) and massive urban development (hence a large thermal mass), so that heat storage is likely to be a significant part of the overall surface energy balance.

2.2 *Field Measurements*

Fast- and slow-response instruments used to conduct energy balance measurements were mounted on a tower which was erected on the roof of a building in the city center of Marseille. Observations were performed in the constant flux layer between 35-44 m above street level, thereby eliminating the influence of individual surface

Corresponding author address: Sarah M. Roberts, Dept. of Geography, University of British Columbia, #217 – 1984 West Mall, Vancouver, B.C. Canada V6T 1Z2
E-mail: sroberts@geog.ubc.ca

roughness elements. Net all-wave radiation (Q^*), turbulent sensible heat flux (Q_H) and turbulent latent heat flux (Q_E) were directly measured using standard radiometric and eddy covariance techniques and ΔQ_S is calculated as the residual in the measured surface energy balance (see Roberts *et al*., 2003). Results presented here are from an eight-day period during the ESCOMPTE-UBL campaign (Mesteyer and Durand, 2002), during the summer of 2001, from July 4th to July 11th.

2.3 *Modeling Approach*

The Town Energy Balance model is implemented to examine the relative sensitivity of surface sensible heat exchanges to various meteorological, geometric, and surface thermal properties. TEB couples the micro- and meso-scales and represents the urban energy budget in meso-scale atmospheric models (Figure 2). TEB uses local canyon geometry together with surface and substrate radiative, thermal, moisture and roughness properties to simulate the effects produced by the presence of buildings. The urban system is simulated by calculating individual energy balances for walls, roads, and roofs, which are then integrated to resolve a local-scale surface energy balance.

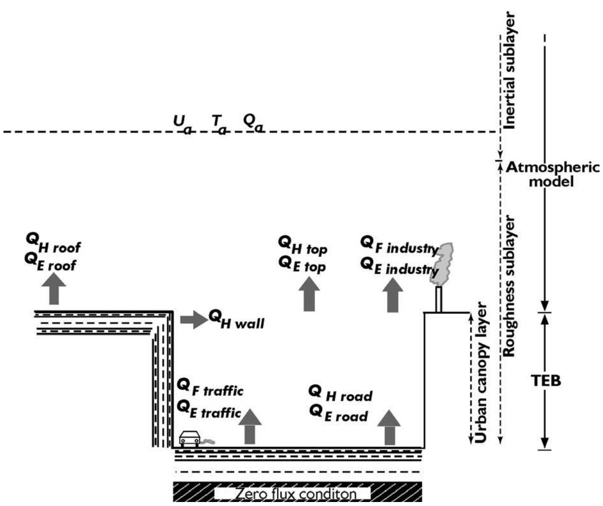

Figure 2 Representation of the individual surfaces for which energy budgets are resolved by TEB. The scale on the right shows the scale of the model, relative to atmospheric layers and meso-scale models.

Source: Modified after Masson *et al*., 2002.

Table 1 provides the input parameters used to initialize the scheme. Meteorological and incoming radiation observations taken from the top of a measurement tower were used to force the model with a 30-minute time step. Given the high volume of vehicular traffic at this site, an anthropogenic heat flux term, Q_F, is included in the simulations. Because this term was not directly measured, it is estimated following the method of Grimmond (1992).

Table 1 Surface cover fractions and TEB input parameters for the static modeling domain (500 m radius around the observation tower) used in the present study.

Parameter	Input Value
Cover fractions	
Natural cover	0.160
Water	0.000
Urban cover	0.840
Building fraction	0.560
Road fraction	0.280
Geometric Parameters	
Building height	15.6 m
Building aspect ratio	0.78
Canyon aspect ratio	2.01
Roughness length	1.90 m
Road Properties	
Material	asphalt and concrete over dry soil
Albedo	0.08
Emissivity	0.94
Momentum roughness length	0.05 m
Roof Properties	
Material	tile or gravel over concrete, wood and insulation
Albedo	0.22
Emissivity	0.90
Momentum roughness length	0.15 m
Wall Properties	
Material	stone and wood shutters
Albedo	0.20
Emissivity	0.90
Momentum roughness length	0.15 m

The model has been independently evaluated using measured fluxes from three dry sites – central Mexico City, a light industrial site in Vancouver, British Columbia (Masson *et al*., 2002) and the city center of Marseille, France (Lemonsu *et al*., 2003). At these sites, TEB simulated net radiation to within 10 W m^{-2} and its partitioning into turbulent and storage heat fluxes to within a few tens of W m^{-2}.

The degree to which sensible heat partitioning is impacted by increased or decreased wind speed is first examined. Aside from wind speed modifications, all surface property, radiometric, and meteorological input parameters are held constant in these simulations. The model is forced with measured hourly wind speed data over the eight-day period (Figure 3). The original forcing file was modified by multiplying every hourly measurement by a fraction or a multiple of its original value.

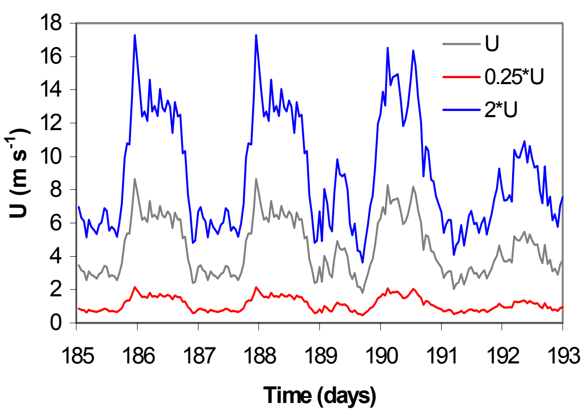

Figure 3 Time series of reference wind speed (U) and the range of modified wind speeds (0.25*U, 2*U) used to force TEB. All data are hourly averages.

Simulations to investigate the relative sensitivity of factors relating to urban geometry and surface thermal and radiative parameters were performed by modifying the input parameters given in Table 1.

3. RESULTS AND DISCUSSION

3.1 *Simulated Energy Balance*

Because Lemonsu *et al*. (2003) performed a detailed analysis of the ability of TEB to accurately simulate the surface energy balance at this site in central Marseille, this paper will not include a detailed discussion of those results. Table 2 gives the performance statistics of the scheme over the pertinent observation period. Results herein focus on the simulated behavior of the energy storage flux term (ΔQ_S) and are shown as biases (= reference simulation – modified simulation). In these plots, positive biases in the daytime indicate less energy taken up by the substrate. Whereas, because the nighttime ΔQ_S flux is away from the surface, positive biases at night indicate larger energy releases than the reference simulation.

Table 2 Performance statistics for mean values of the surface energy balance modeled by the TEB scheme. Bias = TEB – OBS. All units are W m^{-2}. Flux values are hourly averages over YD 185 – 193.

		Q^*	Q_H	Q_E	ΔQ_S
Overall Period	OBS	154	159	12	-17
	TEB	132	112	18	9
	Bias	-22	-47	6	26
	RMSE	51	75	52	78
Daytime	OBS	343	263	30	51
	TEB	315	189	33	97
	Bias	-28	-74	3	47
	RMSE	66	100	58	101
Nighttime	OBS	-69	36	-8	-97
	TEB	-83	22	1	-96
	Bias	-14	-14	9	1
	RMSE	23	24	47	38

3.2.1 *Simulated Sensitivity to Wind Speed*

Figure 4 shows the time series of ΔQ_S due to altering the strength of the flow regime at this site. The general behavior is as expected; more energy uptake by the urban surface under weaker daytime flow and less conduction to the substrate with stronger daytime flow. Conversely, at night, weaker wind speeds and greater accumulation of daytime energy facilitate enhanced sensible heat exchange between the surface and the atmosphere, i.e. greater nocturnal ΔQ_S release. Consistently stronger flow, on the other hand, results in less energy being released to the atmosphere at night, due to reduced daytime energy uptake by the substrate.

3.2.2 *Simulated Sensitivity to Urban Geometry*

Canyon aspect ratio (*H*/*W*) is modified by adjusting the average building height and then entering the desired *H*/*W* (reference value given in Table 1). This procedure ensures that canyon width remains constant between runs, so that only changes to the wall surface area in contact with the atmosphere are considered.

Most of the time through the night, *H*/*W* values less than the reference simulation show positive

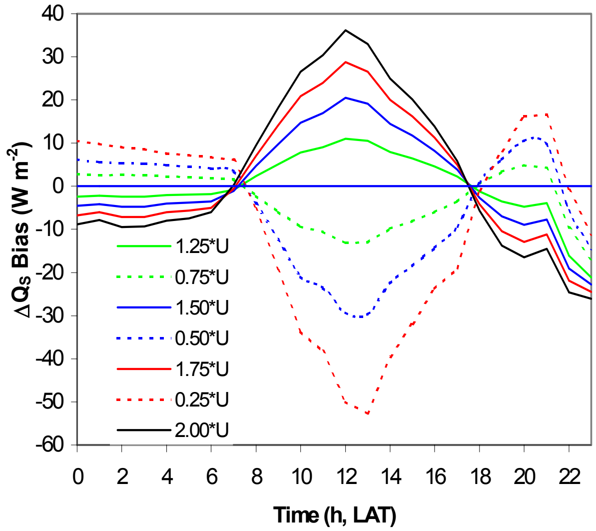

Figure 4 Ensemble diurnal time series of simulated ΔQ_S bias due to wind speeds that are weaker and stronger than the reference (U).

biases, indicative of enhanced nocturnal storage release (Figure 5). This is probably related to less nocturnal trapping of heat by radiation within the urban canyon, due to the considerably smaller wall surface area and hence increased sky view factors. Also in this configuration, heat is more

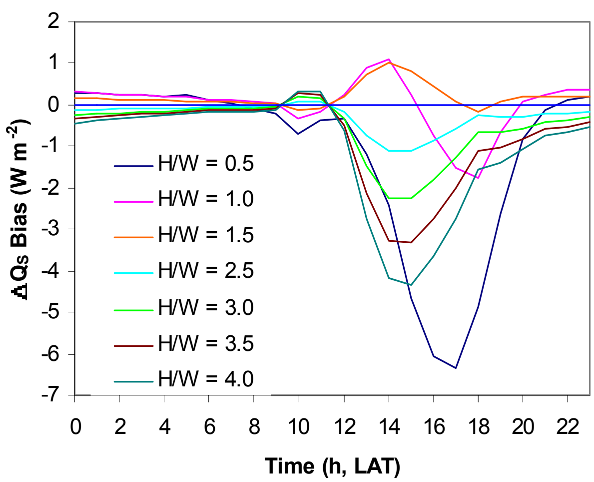

Figure 5 Diurnal ensemble time series of ΔQ_S bias for TEB simulations due to varying the canyon aspect ratio (H/W).

effectively stripped from the surface to the atmosphere above, because the local-scale flow is better able to penetrate into the canyon airspace, i.e. the flow can be categorized more appropriately as 'wake interference,' rather than 'skimming,' flow (Oke, 1989). These results are consistent with those of Masson *et al*. (2002), who found that modifications to the canyon aspect ratio in simulations of central Mexico City and Vancouver (light industrial) had little effect, on the order of ~2%, on diurnal energy uptake/release.

The impact of altering the percent plan area occupied by buildings, while holding the average building height and canyon aspect ratio constant, has a larger impact on local-scale ΔQ_S partitioning than modifications to canyon geometry alone (Figure 6). In this set of simulations, surface thermal and radiative parameters, together with plan area of vegetation and water, remain unchanged, so that the proportion of impervious ground and buildings used in the final local-scale surface energy balance are the focus.

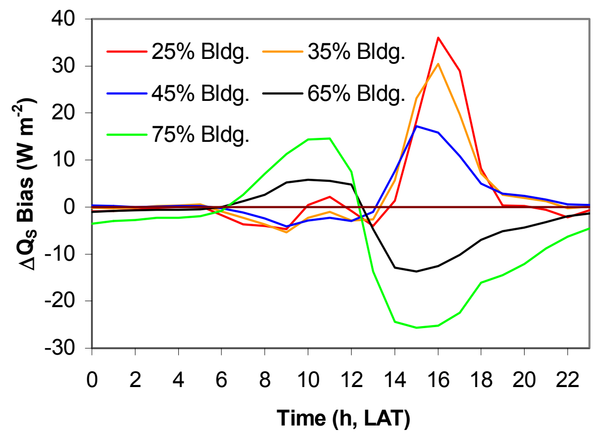

Figure 6 Diurnal ensemble time series of ΔQ_S bias for TEB simulations when the plan area of buildings is varied.

Building plan areas greater than the reference value take up less energy in the morning but compensate for that deficit with positive energy storage flux in the afternoon that is greater than the reference simulation. The opposite behavior occurs when the plan area of buildings is smaller than the reference simulation. A configuration containing less buildings and more road surfaces stores slightly more heat in the early to mid-morning period but then the uptake decreases in the afternoon hours (positive bias). Such a diurnal response is the combined effect of the thermal behavior of the materials and solar geometry. In essence, when more building volumes/roof surfaces are considered in the final integrated surface energy balance, more energy uptake occurs and this is primarily in the afternoon. Having fewer canyons over the modeling domain thereby enhances the role of roofs in controlling sensible heat sharing between the built surface and the air. A configuration such as this, when the majority of horizontal or near-horizontal surface areas considered are not susceptible to shading, minimizes the impacts of solar geometry resolved by TEB. Differential surface heating caused by shading was illustrated by Masson *et al.* (2002). They show that increasing the plan area of buildings decreases average road temperature, while increasing average roof temperature (changes to wall temperatures are not reported). At night, when the effects of shortwave radiative forcing are absent, the simulated ΔQ_S between runs nearly converge (bias ~ 0 W m^{-2}).

3.2.3 *Simulated Sensitivity to Surface Radiative Properties*

When considering the relative impacts of surface radiative parameters, the largest biases occur in the daytime hours due to higher surface albedo values (Figure 7). Less absorption of incident solar radiation by the surface means less total energy is accumulated in storage over the day. Consequently, proportionately less energy is lost to the atmosphere at night than the reference. Varying radiative parameters results in differences of less than 5% in $\Delta Q_S/Q^*$ between simulations. Changes to roof albedo show the greatest overall sensitivity. Although not shown here, higher roof albedos result in average roof temperatures more than 1 K below the reference value between simulations. The is consistent with results of simulations in Mexico City and Vancouver (Masson *et al.*, 2002). This degree of sensitivity is expected, as the highly exposed and nearly horizontal roof surfaces are not involved in canyon trapping (Masson *et al.* 2002). The built-up nature of this site lessens the influence of the road surface albedo, because roads are rarely exposed to direct incident solar radiation. Similarly, solar geometry is the controlling mechanism when a higher wall albedo is input. The time series plot of ΔQ_S bias associated with higher wall albedos shows a distinct bimodal signature, with peaks in positive biases (signifying the greatest departure from the reference value and less ΔQ_S uptake) occurring at sunrise and again in later afternoon. These maxima correspond to times when the vertical wall surface are most exposed to direct solar radiation, so the effects of surface albedo are realized.

The greatest departures from the reference simulation occur with the lightest colored surfaces (α = +0.20 from reference albedo) and when the integrated town (complete built surface area or roads, walls, and roofs) albedo value is increased.

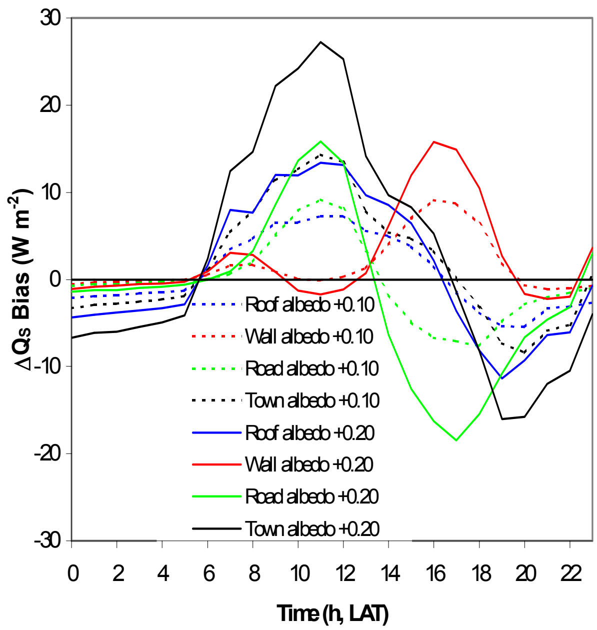

Figure 7 Diurnal time series of energy storage biases for varying surface albedos. Here, 'Town' refers to complete surface area of built elements (roads, wall, roofs).

Lowering the surface emissivity does little to impact the local-scale surface energy balance at this site, with biases < 3 W m^{-2} at all times during the day and night (not shown).

3.2.4 *Simulated Sensitivity to Surface Thermal Properties*

Greater sensitivity was found when facet surface thickness was altered (Figure 8). Modifications were chosen so as to maintain consistency with simulations performed by Masson *et al.* (2002) for sites in central Mexico City and Vancouver.

For the most part, the bias associated with halving the road thickness straddles 0 W m^{-2} until the late afternoon-early evening period, when positive biases occur. The substantial positive bias in the afternoon, when ΔQ_{SREF} refers to a period when the thinner road surface configuration stores a few tens of W m^{-2} more than the reference case. Thinner road surfaces, then, are more thermally responsive later in the day, when the oblique solar path allows results in lower-canyon exposure. Thinner roads decrease the integrated $\Delta Q_S/Q^*$ by 2% in the daytime and make up that difference by releasing 2% less available radiant energy at night. Overall, reducing the road thickness by one-half results in 4% less of the available radiant energy partitioned into storage.

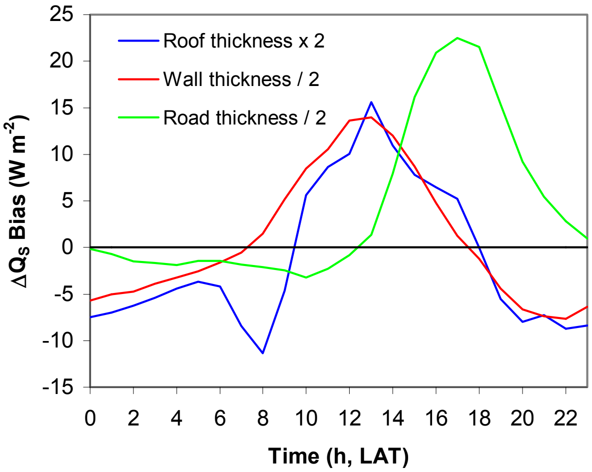

Figure 8 Diurnal time series of energy storage biases due to varying the surface (wall, roof, and road) thickness.

Modifying the wall thickness to one-half the reference value results in approximately the same magnitude of bias in the daytime as at night. Consequently, there is little overall diurnal bias. The approximate symmetry of bias about solar noon is a function of TEB's simple urban geometry formulation, which treats all possible canyon orientations with the same probability of occurrence. Thinner walls do little to modify the amount of available radiant energy partitioned into storage: 1% less uptake overall, with 2% less daytime uptake, and 4% less nocturnal release.

When roofs are made twice as thick as those in the reference simulation, slightly more energy (just over 1 W m^{-2}) is partitioned into storage over the diurnal period. When the proportion of available radiant energy taken up by storage (+1% in the daytime, -1% during the night) is considered, the impacts are less than those simulated for Mexico City (-4% in the daytime) and Vancouver light industrial (+2% in the daytime), where sites at which roof surfaces are constructed of materials with slightly greater heat capacities.

5. CONCLUSIONS

The sensitivity analyses discussed in this paper reveal that the wind speed at this site plays the most significant role in surface-atmosphere sensible heat exchanges. Presumably, this is because the flow regime greatly dictates the degree of surface-atmosphere coupling, which in turn, determines the relative importance of energy conduction/convection processes. Some bias exists when urban geometry at this site is modified, but the simulated impacts are not as pronounced as in the case of wind speed modifications. ΔQ_S partitioning was impacted to a lesser extent by increased built surface albedos and modifications to thermal parameters (represented as surface thickness). Similar to the conclusions of Masson *et al*. (2002), adjustments to surface emissivity was found to generate very little bias between simulations.

5. ACKNOWLEDGEMENTS

Funding for this research has been provided by the Natural Sciences Engineering Research Council of Canada, the Canadian Foundation for Climate and Atmospheric Sciences, the National Science Foundation, Centre National de Recherches Météorologique (Météo-France), and Centre National de Recherches Scientifiques de France.

6. REFERENCES

Grimmond, C.S.B., 1992: The suburban energy balance: methodological considerations and results from a mid-latitude west coast city under winter and spring conditions. *Int. J. Climat.* **12**, 481-497.

Lemonsu, A., C. S. B. Grimmond and V. Masson, 2003: Modelling the surface energy balance of a core of an old Mediterranean city: Marseille. *J. Appl. Meteor.*, *in press*.

Masson, V., 2000: A physically-based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Meteor.*, **94**, 357-397.

Masson, V, C. S. B. Grimmond and T. R. Oke, 2002: Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *J. Appl. Meteor.*, **41**, 1011-1026.

Mesteyer, P.G. and P. Durand, 2002: The UBL/CLU-ESCOMPTE experiment: description and first results. *Preprints Fourth Symposium on the Urban Environment.* Amer. Meteorol. Soc., Norfolk, VA, 19-20.

Oke, T.R., 1988: Street design and the urban canopy layer climate. *Energy Build.*, **11**, 103-113.

Roberts, S.M., T.R. Oke, J.A. Voogt, C.S.B. Grimmond, and A. Lemonsu, 2003: Energy storage in a European city centre. *Proceedings, Fifth International Conference on Urban Climate*, Int. Assoc. for Urban Climate., Łódź, Poland, 1-5 September 2003.