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SENSITIVITY TESTING OF AN URBAN SURFACE SCHEME COUPLED TO A 1-D BOUNDARY LAYER MODEL

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1. INTRODUCTION

Many applications would benefit from accurate simulation of energy exchanges and temperature evolution in urban areas. Such exchanges are very complex in practice, and require an understanding of urban surface-boundary layer coupling in addition to urban canopy processes. Recently, urban surface parameterizations of greater complexity have been developed with the intent of being coupled to atmospheric models (Masson 2000; Martilli *et al*. 2002), thus providing the tools to fully simulate urban-atmosphere interactions. However, with greater complexity comes greater demand for input parameters and initial conditions. Input parameter uncertainties combined with the need to determine model robustness dictates that model sensitivity to input parameters must be determined.

Urban surface parameterization sensitivity has largely been determined in coupled simulations of hypothetical situations (Martilli 2002), or offline for real situations, that is, without feedback from an atmospheric model (Masson *et al*. 2002). Rural forcing data has sometimes been used in offline studies. Pitman (1994) suggests that the offline approach to surface scheme sensitivity analysis can be unreliable and uses a column model to obtain better sensitivity estimates. Here, we couple the Town Energy Balance (TEB) urban surface scheme of Masson (2000) with a simple first-order column model to simulate the energy balance over a period of two days at a dense urban site (Sperstrasse) in Basel, Switzerland (47.57 ^{o}N, 7.58 ^{o}E). Subsequently, we conduct a limited number of sensitivity analyses both with and without feedback from the column model to assess the importance of atmospheric feedback. The latter simulations are forced by model output from a base case simulation, rather than by observations. In this paper we focus on the daytime period when thermal forcing dominates.

2. MODELLING APPROACH

A combination of models provides a simple but relatively complete description of the boundary layer and surface radiative, heat, moisture and momentum exchanges for clear sky conditions. The Oregon State University (OSU) boundary layer model (Troen and Mahrt 1986) parameterizes mixing within the boundary layer, while TEB and the soil-vegetation scheme of Mahrt and Pan (1984) (MP84) parameterize surface and sub-surface interactions. The Roach and Slingo (1979) 5-band longwave scheme (RS79) accounts for longwave exchanges and longwave cooling within the atmosphere. A simple broadband scheme parameterizes the incoming direct and diffuse solar radiation at the urban surface. TEB is updated to include the modifications described in Masson *et al*. (2002) and Lemonsu *et al*. (2002).

OSU uses a simple 1-D K-profile parameterization of mixing. The inclusion of a countergradient term accounts for non-local mixing during convective conditions. Additionally, it mixes momentum given a mean geostrophic wind speed (or equivalently, mean horizontal pressure gradient) as input. Subsidence is important for maintaining the capping inversion during convective conditions in OSU simulations, and an input profile (peak –0.012 m s^{-1} near 2 km) is estimated and remains constant for the duration of the simulation.

Surface boundary conditions to the OSU boundary layer model are supplied by TEB and MP84 for urban and natural areas, respectively. Both schemes require temperature, wind speed and mixing ratio at the lowest OSU model level, in addition to longwave flux from RS79 and solar, as input. They output sensible heat, latent heat, and momentum fluxes to OSU, weighted by the urban and natural fractions. Thus, OSU surface boundary conditions and eddy diffusivities are dependent on weighted average surface scheme output fluxes and temperatures.

MP84 is run as a simple 3-layer soil model with a single vegetation layer, and accounts for evapotranspiration and thermal and water storage. In urban simulations with natural areas, MP84 is assumed to absorb, reflect, and emit radiation as if it was on the canyon floor, but is otherwise treated independently from TEB (i.e., in its interactions with OSU).

Advection can be a large, even dominant term in the energy balance, particularly where substantial horizontally gradients exist, for example near urban-rural boundaries. Advection is simulated by assuming that the rural simulation provides a reasonable approximation the atmospheric profile upstream of the city from any given direction. A simple relaxation-type advection equation is employed:

$$dT_{urb}(z)/dt = M(z)\ (T_{rur}(z) - T_{urb}(z)) / \Delta x \qquad (1)$$

where Δx is the approximate minimum distance from Sperstrasse to the rural-urban boundary in most directions (3000 m is used here), $T_{rur}(z)$ and $T_{urb}(z)$ are the rural and urban temperatures at height z, respectively, and $M(z)$ is the wind speed at height z as calculated in the urban simulation. For the average daytime mixed layer windspeeds of ~4 m s^{-1} during this simulation, this translates into a relaxation time $\tau = \Delta x / M(z)$ of approximately 12-13 minutes, which is larger by a factor of 2.5 than that chosen by Clark and Hopwood

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(2001) as a free atmosphere value. We assume internal boundary layer (IBL) development is small since Basel is limited in horizontal extent, and its mean surface properties are likely closer to those of rural surfaces than the dense urban surfaces at Sperstrasse. It is worth noting the paucity of quantitative relations for rural-urban IBL development, which has received virtually no attention in comparison with water-land IBL development. We additionally assume that the rural profile advected is representative of the boundary layer outside the city in all directions, therefore we are not accounting for large-scale gradients and advection with this term. The intent of this advection term is not to model the impacts of advection precisely, but rather to estimate the bulk impacts of the largest energy balance term ignored in our 1-D boundary layer model.

3. SIMULATION DEVELOPMENT

Observations from the densely developed Sperstrasse site (λ_p = 0.54, z_H = 14.6 m) of the BUBBLE campaign (Rotach 2002) in Basel, Switzerland were chosen for comparison with the model. Select geometrical, radiative and thermal parameters input to TEB are detailed in Table 1. Roof surfaces are clay tile and gravel over coal tar, wall surfaces are concrete, glass and brick, and roads are asphalt. Hourly anthropogenic heating is estimated to be half that of Chicago as determined by Sailor and Lu (2004).

A 48-hour clear sky period beginning at 0000 LST May 30, 2002 is modelled. Initial profiles of temperature, mixing ratio and wind speed are provided by a sounding from Payerne airport (LSMP), Switzerland (46.82 ^{o}N, 6.95 ^{o}E) taken at 0000 LST May 30, 2002. Temperatures in the lower 2 km of the sounding are corrected assuming a 6 K km^{-1} lapse rate to account for the LSMP-Basel elevation difference. Initial surface temperatures are set iteratively by running the model over several days and extrapolating surface temperature trends back to the start time.

A rural simulation is performed using initial soil moisture as a tuning parameter to obtain low-level temperature and flux results in good agreement with rural observations near Basel, specifically at the Grenzach and Village Neuf observational sites. The intent of these simulations was to obtain realistic rural boundary layer profiles for advection, not to model the rural energy balance. The original (base case, hereafter 'bc') urban simulation is subsequently re-run with advection from the rural θ and q profiles (hereafter the 'adv' simulation), as described in the previous section. In all simulations temperature and mixing ratio are constantly relaxed towards the 0000 LST June 1, 2002 LSMP sounding profile with τ = 1 day in the free atmosphere (i.e., above the mixed or residual layer) and τ = 10 days below to account for diabatic heating and synoptic- and meso-scale advection.

Mean bias error (MBE) and root mean square error (RMSE) are computed for Q*, Q_h, Q_e, and T_{air} at 31 m. Additionally, RMSE is divided into its systematic ($RMSE_s$) and unsystematic ($RMSE_u$) parts to estimate the relative magnitude of systematic (corrigible) error and unsystematic error, the latter being a measure of potential model accuracy (Willmott 1982).

Table 1: Selected input parameter values. *Thermal parameters listed in order from the surface layer through to the interior layer.

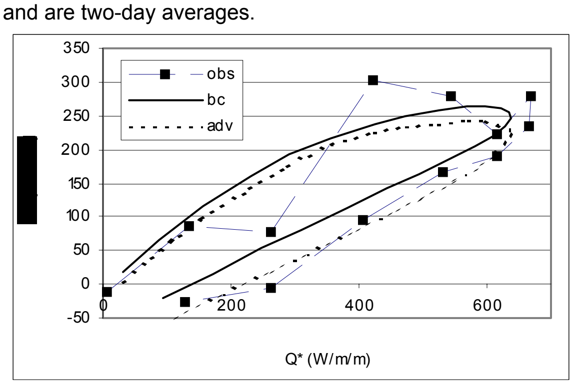
Parameter	Unit	Numerical Value	
Geometric Parameters			
Building Fraction	–	0.54	
Building Height	m	14.6	
Wall/Plane Area Ratio	–	0.92	
Canyon Aspect Ratio	–	1.00	
Town Roughness Length	m	0.88	
Roof Roughness Length	m	0.15	
Road Roughness Length	m	0.05	
Radiative Parameters			
Roof albedo	–	0.11	
Wall albedo	–	0.25	
Road albedo	–	0.08	
Thermal Parameters*			
Roof layer heat capacities	MJ m^{-2} K^{-1}	0.017, 0.005, 0.008, 0.070	
Wall layer heat capacities	MJ m^{-2} K^{-1}	0.014, 0.054, 0.134, 0.028	
Road layer heat capacities	MJ m^{-2} K^{-1}	0.019, 0.078, 0.039, 1.316	
Roof layer thermal conductivities	W m^{-1} K^{-1}	0.61, 0.13, 0.09, 0.98	
Wall layer thermal conductivities	W m^{-1} K^{-1}	1.07, 1.08, 1.07, 0.65	
Road layer thermal conductivities	W m^{-1} K^{-1}	0.75, 0.75, 0.93, 0.28	
Temperature Initialization			
Building Interior Temperature	^{o}C	19.0	
Deep Soil Temperature	^{o}C	12.0	
Natural Area		Rural sim.	Urban sim.
Natural fraction		1.0	0.16
Albedo	–	0.21	0.20
Roughness length	m	0.10	0.50
Wilting Point	m^{3}m^{-3}	0.12	
Soil Layer Depths	m	0.02, 0.08, 0.95	
Initial Soil Moisture	m^{3}m^{-3}	0.19, 0.22, 0.25	0.28, 0.29, 0.30

A subset of the sensitivity simulations performed by Masson *et al.* (2002), in particular those demonstrating maximum sensitivity, were re-run with respect to the Basel base case. However, the 0.16 vegetation fraction was converted to road so as to examine TEB's sensitivity uncomplicated by that of the vegetation scheme while still preserving the H/W ratio. The impact on canyon air temperature, maximum Q*, and sensible/storage heat flux partitioning were examined. Subsequently, these simulations were rerun without feedback from the atmosphere (i.e. without OSU and RS79). Thus, inputs to TEB from the base case (non-advective) simulation were saved and used as forcing in each sensitivity run, mimicking the use of observed tower data to force TEB for offline sensitivity studies as in Masson *et al.* (2002). This allows for a comparison of modelled parameter sensitivity between offline and fully coupled simulations.

4. RESULTS AND DISCUSSION

Figure 1 and Table 2 demonstrate that the model captures the net radiation and storage/turbulent partitioning reasonably well in both the base case and advection simulations. Partitioning of the turbulent flux is not as well handled. Modelled Q_e is roughly half of the observed value while modelled Q_h is too large by a similar absolute magnitude, suggesting the latent/sensible heat partitioning in the MP84 model is incorrect (Table 2, Figure 2). There are many possible explanations, including the neglect of horizontal microadvection (e.g. the 'oasis effect') and of anthropogenic Q_e in the model, and underestimation of the total amount of vegetation. Indeed, comparing the observed Bowen ratio of ~3 (i.e., Q_e / (Q_e + Q_h) = 0.25) with the 'natural' fraction of 0.16 suggests that at least one of these factors must play a role. The $RMSE_s$ and $RMSE_u$ values in Table 2 indicate that most of the model-observation disagreement in Q_h results from unsystematic variation in the observations, that is, variation that is beyond the ability of the model to capture. Q_e and T_{air} have large systematic disagreements, which, for T_{air}, appear to be largely corrected by advection. It should be noted that no attempt was made to weight model input parameters by prevailing wind direction, and thus disagreement may result partly from the use of model parameters representative of the area surrounding the tower but not necessarily of the source areas influencing the observations.

Figure 1: Observed (obs), base case (bc), and base case with advection (adv) storage heat flux vs. net radiation. Observed values are residuals. Values are for hours 0600 – 1800 LST and are two-day averages.

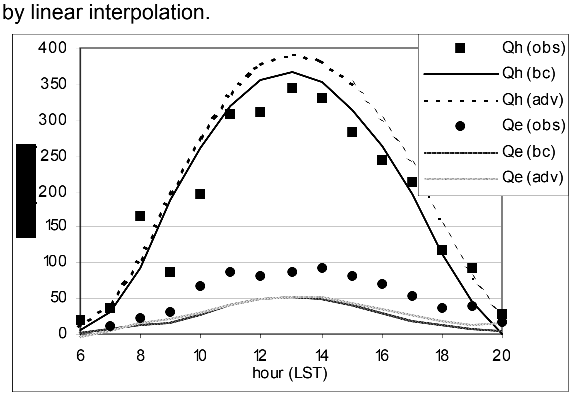


Advection from the rural simulation 'brings' cooler, moister air over the city, worsening slightly the modelled Q_h/Q_e partitioning comparison with the observations. However, advection serves to remove the bias and drastically reduce the RMSE in air temperature, suggesting it is important in the observed boundary layer energy balance. Observations of near surface wind direction and speed (not shown) both show a clear diurnal oscillation suggesting that along-valley slope flows dominate the near-surface wind regime, and therefore that advection will play a substantial role in the urban energy balance. Basel is relatively small in horzontal extent, and thus full boundary layer adjustment to urban surface properties is unlikely to occur.

Table 2: Performance statistics of combined model for 31 m fluxes and air temperatures during the daytime (n = 26 for Q_h, n = 18 for Q_e; n = 146 for Q*; n = 73 for T_{air}). bc = base case; adv = base case with advection. All values are daytime averages over 2 days with the exception of T_{air} (1 day). Q*, Qh, Qe in W m^{-2} K^{-1}, T_{air} in °C.

		Q*	Q_h	Q_e	T_{air}
bc	Model	415.3	219.6	27.5	20.9
	MBE	-13.6	+15.9	-25.3	+2.0
	RMSE	37.8	57.8	32.5	2.1
	$RMSE_s$	26.7	16.4	31.5	2.1
	$RMSE_u$	26.7	55.4	8.1	0.4
adv	Model	418.7	242.5	29.0	17.9
	MBE	-10.2	+38.7	-23.8	-0.2
	RMSE	36.0	66.9	30.1	0.6
	$RMSE_s$	26.9	38.7	29.1	0.4
	$RMSE_u$	23.8	54.5	7.6	0.4

Figure 2: Observed (obs), base case (bc), and base case with advection (adv) 2-day average daytime sensible and latent heat fluxes. Some observed values are missing and generated by linear interpolation.



Selected sensitivity simulations (Table 3) performed offline yield similar results for 'Max Q*' and 'Daytime Q_s/Q*' to those obtained offline by Masson *et al*. (2002) for Mexico City historic core and Vancouver Light Industrial. Sensitivities of maximum Q* and daytime Q_s/Q* with atmospheric coupling are generally slightly reduced in magnitude compared their offline values. The reduction of town z_0 by half is the exception, showing the opposite sensitivity with atmospheric coupling (the negative sensitivity in Q_s/Q* is approximately –0.003 but rounded to 0.00 in Table 3).

Town z_0 serves two purposes in TEB: it regulates both the town momentum flux and the transfer of heat between the canyon and the atmosphere. The former does not affect the energy balance offline, but does indirectly in coupled mode since surface momentum flux affects boundary layer eddy diffusivities in OSU.

Sensitivity to a large change in roof albedo (+0.50) is modelled to better show the difference between coupled and offline results. Net radiation sensitivity is similar, but the daytime flux partitioning is very different since the offline study heats up the atmosphere as though no albedo modification had occurred and erroneously dampens Q_h. This highlights the importance of coupling for impact studies. Roof albedo has been targeted as a potential cooling mechanism in cities, so we include the impact on modelled canyon temperature (T_{can}) for both the base case and advection case. The former could be interpreted as a maximum impact, while the latter may be somewhat more realistic. Canyon temperature sensitivity is zero in those offline simulations whose modified parameter does not directly affect the canyon energy balance in TEB (i.e. all but town z_0), and is only non-zero in the coupled simulations due to indirect coupling between the roof and canyon via the boundary layer model.

Table 3: Sensitivity analysis due to varying TEB parameters from the reference base case (bc) and the reference base case with advection (adv). Rows in grey are forced by the reference atmosphere (i.e. offline); all remaining rows interact with the model atmosphere. Values are two day averages.

	Max Q^* (W m^{-2})	Daytime Q_s/Q^*	Max T_{can} (^oC)	Average Daytime T_{can} (^oC)
Reference (bc):	636	0.46	27.2	22.5
Roof albedo +0.10	-37	+0.01	-0.7	-0.5
Roof albedo +0.10	-40	+0.02	0.0	0.0
Roof thickness x 2	+1	+0.01	-0.1	-0.3
Roof thickness x 2	+1	+0.02	0.0	0.0
Roof z_0 / 5	-33	+0.04	-0.2	-0.2
Roof z_0 / 5	-30	+0.04	0.0	0.0
Town z_0 / 2	+7	0.00	+0.4	+0.4
Town z_0 / 2	-1	+0.01	+0.6	+0.5
Roof albedo +0.50	-187	+0.06	-3.7	-2.8
Roof albedo +0.50	-201	+0.17	0.0	0.0
Reference (adv):	637	0.39	22.8	19.1
Roof albedo +0.50 (adv)	-183	+0.10	-0.6	-0.7
Roof albedo +0.50 (adv)	-198	+0.13	0.0	0.0

The results presented in this paper suggest that offline sensitivity results often approximate the true sensitivity, and in many cases probably provide an upper bound to the sensitivity, since atmospheric feedbacks will tend to reduce any sensitivities. However, model sensitivity to parameters whose full impact on the energy balance is not taken into account in offline studies may not even have the correct sign (e.g. town z_0 in Table 3). Additionally, the impacts of large modifications of sensitive variables will likely be significantly overestimated with an offline approach.

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