ASSESSING THE ERROR FROM FAILURE TO ACCOUNT FOR URBAN MICROCLIMATE IN COMPUTER SIMULATION OF BUILDING ENERGY PERFORMANCE

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ABSTRACT

The paper examines the importance of using site-specific data in computer simulation of building energy performance. The CAT (Canyon Air Temperature) computer model, which is designed to predict site-specific air temperature in an urban street canyon for extended periods on the basis of data from a reference station exposed to the same meso-scale weather, was used to provide modified input to a series of Ener-Win simulations of the energy performance of a hypothetical office building. The simulations show that, depending on the urban configuration represented by the aspect ratio of the street canyon, the modification to air temperature in many locations may be too large to neglect if the simulation is to be used for realistic design decision making.

INTRODUCTION

Site-specific climate knowledge is essential for the development of a building design that responds to the local environment, for accurate design of HVAC systems and for the development of efficient control strategies. Most building simulation software comes with inbuilt climate data files; either “real” data compiled from stations such as airports or calculated “synthetic” data. In each case, the climate data is assumed to be representative of the surrounding area. However, evidence of urban modification to weather indicates that the differences between city-centre locations and the typical rural reference sites used by meteorological services are often quite substantial (Oke 1973).

This paper demonstrates the effect of accounting for urban modification to air temperature on the design parameters of an HVAC system in a hypothetical office building. The energy requirement of the building is simulated for three locations representative of three climate types: cool/cold, temperate and hot dry. The locations used are Glasgow-Scotland, Adelaide-Australia and Sde Boqer-Israel.

The urban effects on peak heating and cooling loads as well as on annual energy budget are presented in detail. The procedure is repeated for different street widths characteristic of different city densities, varying the street canyon aspect ratio between 0.25 and 4.0, but keeping the properties of the office building fixed, including the height.

THE CAT MODEL

The CAT (Canyon Air Temperature) computer model (Erell and Williamson 2006) was developed to predict site-specific air temperature in an urban street canyon for extended periods on the basis of data from a reference station exposed to the same meso-scale weather. Such stations are sometimes located at nearby airports or in a semi-rural location outside of the city centre. Each site is described by means of its geometry (height of buildings, if any, and width of street); the albedo and thermal properties of the surfaces; moisture availability; and anthropogenic heat (energy released by human activity, such as vehicular traffic and buildings, as well as metabolic heat). In addition to the description of the two sites, CAT requires as input only time-series of meteorological parameters measured at standard weather stations, and, in addition, solar radiation, typically at hourly intervals. These serve as descriptors of the constantly evolving meso-scale weather. An energy balance is then computed for each of the two sites, taking into account the effects of urban geometry on radiant exchange, the effect of moisture availability on latent heat flux, energy stored in the ground and in building surfaces, air flow in the street based on wind above roof height, and the sensible heat flux from individual surfaces and from the street canyon as a whole. By calculating site-specific modifications to air temperature resulting from the surface energy balance at each of the two sites (reference and urban), the software can predict the evolution of air temperature at the urban site based on measured meteorological parameters at the reference site, in diverse weather conditions and for extended periods.

The CAT model was calibrated and tested using experimental data obtained in an extended monitoring program carried out in Adelaide, South Australia, over a period of nearly one year. Field measurements were carried out at two adjacent street canyons in the urban core, running north-south and east-west respectively, and compared with data recorded at reference sites in a suburban location and at an open park.

The urban sites are about 500 metres from the centre of the business district of Adelaide, and about 1.5km southeast of the Australian Bureau of Meteorology weather station at suburban Kent Town (Figure 1). The open reference site is located in the green belt surrounding the central business district, approximately 2.1km northeast of the city centre.

Figure 1. *Aerial photograph of central Adelaide, showing location of monitoring sites. The area in the photo is the core of the Adelaide metropolitan area, which extends about 20kms east from the Gulf of St. Vincent to the Adelaide Hills, and about 25kms from north to south.*

Data representative of the whole of the study area included global solar radiation; diffuse solar radiation, net all-wave radiation and 'effective sky temperature'. The reference station monitored site-specific dry bulb temperature, relative humidity, wind speed and wind direction. At the urban sites (Figure 2), measurements were made of air temperature at several points in each street cross-section, relative humidity, wind speed and wind direction. Data were sampled at 15-second intervals, and 15-minute averages were computed by electronic data loggers and stored for subsequent retrieval.

After calibration, the model was capable of replicating measured air temperature in the urban street canyons in all weather conditions, including intense nocturnal heat islands in the city of up to 8.6 K and daytime cool islands of up to 3.8K (Erell 2005; Erell and Williamson 2007). Figure 3 shows a comparison of predictions made by CAT with measured air temperature in one of the Adelaide street canyons for a period of ten days, in which weather conditions varied from sunny to overcast with rain. Recent comparisons with measured data in Goteborg (Sweden) and Saloniki (Greece) also show good results (unpublished work in progress).

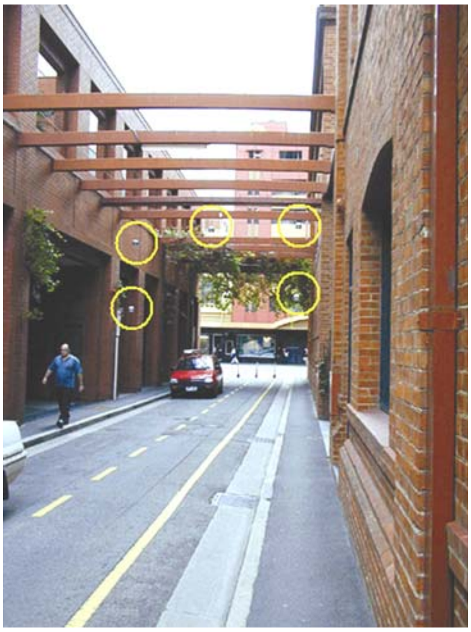

Figure 2*. Urban street canyon monitored. Circles indicate position of temperature sensors in instrument shields.*

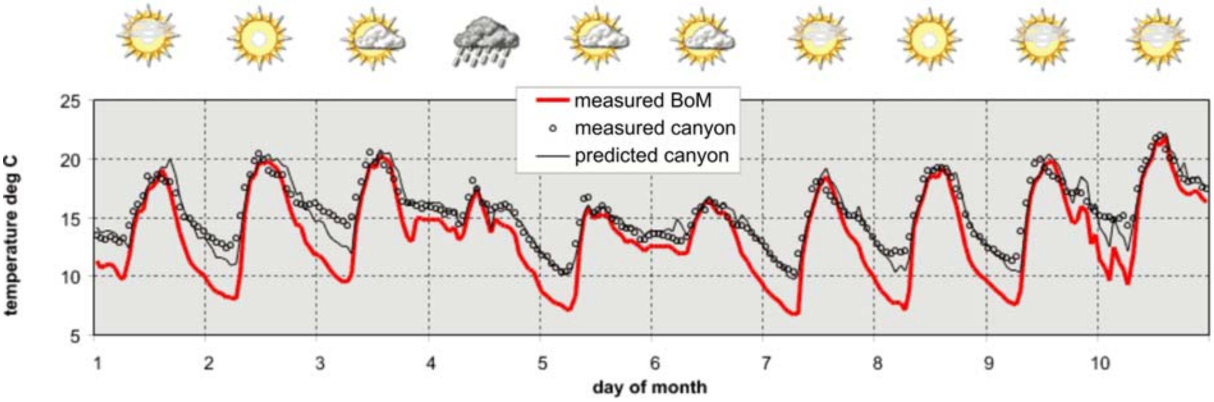

Figure 3*. Comparison of measured air temperature at urban street canyon with temperature predicted by CAT from Bureau of Meteorology (BoM) data for a 10-day period in May, 2000.*

CASE STUDY METHODOLOGY

Modifications to climate input file

The same general methodology was used in each of the study locations to examine the effect of the urban modification of air temperature on the energy performance of a test building. EnerWin whole-building energy simulation software (Degelman and Soebarto 1995) was employed in the investigation which requires input of environmental data in the form of hourly records for an entire year.

For this study, weather data RMY (Reference Meteorological Year) data - Adelaide and TMY (Typical Meteorological Year) data – Glasgow & Sde Boqer in TMY2 format were used. The data were processed to conform to the input format of CAT, and the software was run to produce a time series of predicted air temperature in urban canyons with different aspect ratios.

A number of simulations were conducted for each situation examined. First, the energy performance analysis was carried out using "standard" climate data. This is referred to as the reference situation. The same building was then simulated a second time, using a modified input file with air temperature in a hypothetical urban canyon predicted by CAT in place of measured air temperature data from the "standard" file. The results of the simulations were then compared to assess the effect of urban modifications to air temperature on the energy budget of the building. This process was then repeated, adding the effect of the shading on the study building provided by the canyon configuration.

In all cases, the building height (H) was kept constant at 14 metres, while the width of the street (W) was varied from 3.5 metres to 56 metres (Figure 4).

Like most whole-building simulation software, EnerWin assumes all external building surfaces are exposed to the same ambient air temperature. Although differences in air temperature between streets with different orientations have been shown to be non-negligible (Erell and Williamson 2007), a single value corresponding to the simulated air temperature in a north-south canyon was used in this study as a representative input.

Figure 5 shows the difference in air temperature between the simulated urban environment and the standard weather data for each hour during the entire year, plotted against time of day, for a street with H/W=1. The comparison is instructive: The urban site is warmer than the reference site by up to 6 K at the night, but urban temperatures during the daytime are often cooler - the temperature difference at noon ranges from about 1 K to about –2 K.

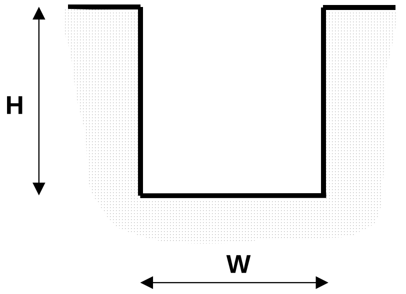

Figure 4*: Schematic section of a generic urban street canyon. In this study, canyon walls were kept at a constant height of H=14m, while the street width was varied from W=3.5m to W=56m. The corresponding aspect ratios (H/W) thus varied from 4 (14/3.5) to 0.25 (14/56).*

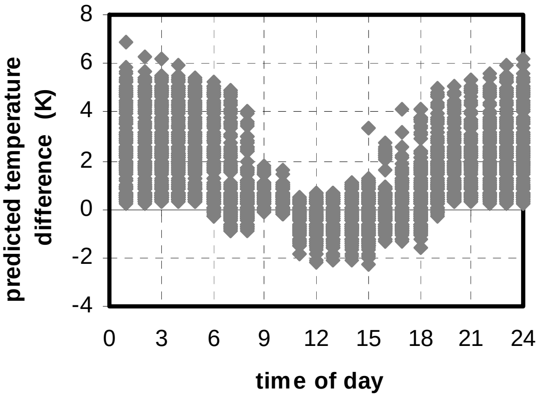

Figure 5: *Diurnal pattern of the intra-urban heat island of Adelaide simulated by CAT from RMY meteorological data, for a street canyon with H/W=1. Negative values indicate the street was cooler than the reference site.*

The urban simulations also demonstrate that in addition to a distinct diurnal pattern, there is a clear seasonal pattern to the temperature difference. Figure 6 shows that during winter (May-Sept), the urban heat island is an almost continuous feature, both day and night, varying only in magnitude. During the rest of the year, and especially during the summer months, the nocturnal urban heat island alternates with a weak daytime cool island. These effects were also seen in the measured data collected as part of a field monitoring experiment (Erell and Williamson 2007). Similar results have been noted in a study of the urban microclimate in the city of Vancouver, Canada (Runnalls and Oke 2000).

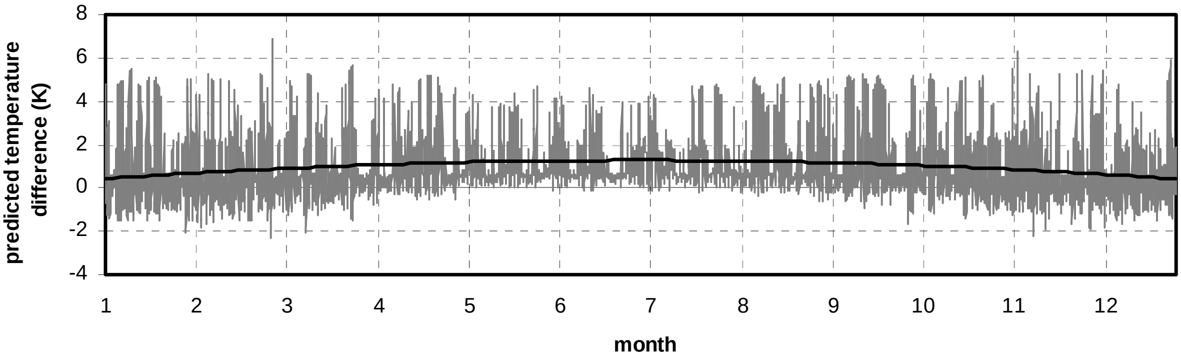

***Figure 6**: Seasonal pattern of the intra-urban heat island of Adelaide simulated by CAT from RMY, for a street canyon with H/W=1. Negative values indicate the street is cooler than Reference data. The time series trend is represented by a thick black line.*

Building description

The building used for evaluation is a typical four-storey development, consisting of public spaces on the ground floor (café, etc) and identical office type accommodation on the upper floors (See Figure 7). Some modifications are made to accommodate the context of each location; an equator facing façade is maintained and the glass area is adjusted to reflect the expectations of the location.

***Figure 7**: View of Case Study Building*

The total floor area of the building is 1430m^2 (about 30m x 12m per floor).

The simulated building has external walls of insulated pre-cast concrete (thermal conductance U=0.68 W m^{-2} K^{-1}), a built-up concrete roof (U=0.28 W m^{-2} K^{-1}) and concrete slab intermediate floors. Windows were taken as double glazed low-e in aluminium frames ($U_{overall}$=2.75 W m^{-2} K^{-1}). An infiltration rate of 0.6 air changes per hour was specified, and in addition, a mechanical ventilation rate of 15 litres s^{-1} person^{-1}. Internal heat gains were calculated taking into account a detailed occupancy schedule specified in the Building Code of Australia. Lighting and equipment introduce an additional load of 15 Wm^{-2}, on average.

Thermostat settings for the simulation were: summer: 24 ^{o}C when the building is occupied and 26 ^{o}C when it is unoccupied; and winter: 21 ^{o}C at all times.

RESULTS

Comparing climatic regions

Intra-urban differences in air temperature are known to be affected by meteorological conditions. For example, intense heat islands are more likely to occur at night in clear sky conditions that promote radiant cooling, if wind speed is very low (Eliasson 1996). Variations among cities or among different locations in the same city may be explained by differences in site exposure to long wave radiant loss, as demonstrated by Oke (Oke 1981).

The combined effect of these factors was investigated by running a series of CAT simulations using as input, weather files from the three study locations with different climatic characteristics: Adelaide, Mediterranean climate with cool, humid winters and warm to hot dry summers, Glasgow, a mild to cold and damp climate and Sde Boqer, in the desert highland of Israel, is generally hot and dry. For each location, the simulations were carried for a street canyon oriented east-west and bordered by buildings with a uniform 14-metre height. The width of the street canyon was varied from 3.5 metres (representing a very narrow alley) to 56 metres, but the properties of canyon surfaces were unchanged throughout the simulation.

Anthropogenic heat input was varied for each canyon width in an attempt to represent a realistic scenario of different development, traffic and pedestrian densities. For the narrow street canyon H/W=4.0 the daytime anthropogenic heat was 54 Wm^{-2} and for H/W=0.25 it was 12 Wm^{-2}. In the CAT model the anthropogenic heat input is reduced during the night time hours and is equivalent to half the peak traffic flow.

Tables 1 and 2 show the average maximum canyon heat island and cool island, respectively, predicted by CAT on the hottest three months in a location.

Table 1: *Average monthly maximum canyon* ***heat*** *island (K) predicted by CAT for different canyon aspect ratios, during the hottest three months of the year.*

Location	**Canyon Aspect Ratio**				
	4	2	1	0.5	0.25
Adelaide	5.9	5.5	5.2	3.7	3.1
Glasgow	4.1	3.8	3.3	2.9	2.4
Sde Boqer	4.6	4.3	3.9	3.6	2.5

Table 2: *Average monthly maximum canyon* ***cool*** *island (K) predicted by CAT for different canyon aspect ratios, during the hottest three months of the year.*

Location	**Canyon Aspect Ratio**				
	4	2	1	0.5	0.25
Adelaide	1.8	1.7	1.6	1.4	1.2
Glasgow	1.1	1.0	1.2	1.1	1.1
Sde Boqer	1.3	1.0	1.0	.8	.6

As expected, the intensity of the urban effect is weakest in Glasgow: Frequent extensive cloud cover and high atmospheric humidity limits nocturnal cooling in both urban and rural locations, reducing the magnitude of nocturnal heat islands. The results are in line with results reported by Watkins et al (2002). In such conditions, the potential for daytime cool islands is also quite small. The effect of canyon aspect ratio on the magnitude of the intra-urban differences in temperature is discernible, but quite small.

Conditions in Adelaide are much more conducive to the formation of intense intra-urban temperature variations: The sky is frequently clear and moisture content is low, especially in summer, promoting the development of both nocturnal heat islands and daytime cool islands. There is a clear inverse correlation between canyon width and heat island intensity. The mean maximum monthly heat island intensity is 5.9 K for a canyon 3.5 metres wide, but only 3.1 K for a street 56 metres wide. The data for Adelaide also highlight a clear seasonal pattern: Intra-urban temperature differences, both day and night, tend to be more pronounced in summer (November-March), and weaker in winter (May-August), when weather is typically much wetter, coupled with frequently windy conditions.

At Sde Boqer, one might have expected to find that conditions even more likely to lead to the formation of intense intra-urban temperature differences. However, although the air is dry and skies are usually cloud free, almost year round, wind speed is rarely low enough to allow the formation of very intense nocturnal heat islands. Low-level turbulence associated with wind induces effective mixing between near-surface and upper level air, as well as the advective transfer of sensible heat. Thus, although similar intra-urban temperature variations may be observed throughout the year – and are largest in winter - the magnitude of these differences is slightly smaller than that predicted for Adelaide.

Peak Loads

In general the effect on peak loads when the air temperature is modified by increasing the density of the urban environment is to decrease the heating load and increase the cooling load. The simulated results for Glasgow and Sde Boqer shown in Figure 8 verify this effect, albeit the changes are relatively small.

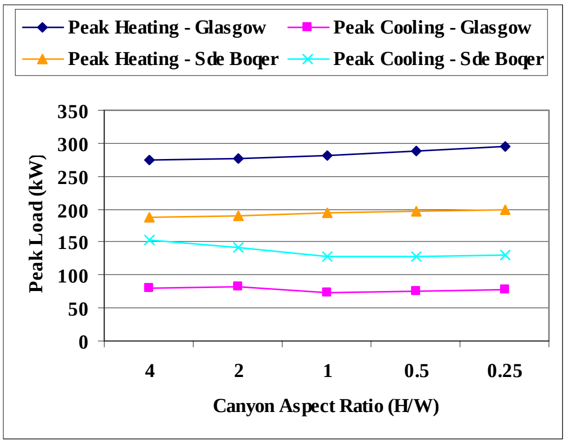

Figure 8: *Peak Heating and Cooling Load Glasgow and Sde Boqer*

The pattern in the peak heating load is not surprising, since the urban fabric has the effect of damping extreme diurnal variations in temperature, reflected in the nocturnal heat island. One might expect a similar effect for the cooling load. In this study, however, the values input for the anthropogenic heat release have outweighed any benefit that might have occurred.

Energy Consumption

Differences in the canyon aspect ratio affect the energy consumption of buildings in a variety of ways. For example, deep canyons restrict natural ventilation; yet they also provide mutual shading for buildings on either side of the street. The net effect of a particular canyon geometry depends on the specific design of a building: Shading by adjacent buildings has little effect if it has small, well-protected windows, while the effect of differences in air temperature may be minimized by increasing thermal insulation of exterior surfaces. Two sets of analyses were made to investigate the influence of varying the canyon ratio: first, with

Table 3: *Annual energy budget for heating and cooling in the three test locations, for different street canyon configurations, as predicted by CAT – NO MUTUAL SHADING.*

	Adelaide			**Glasgow**			**Sde Boqer**		
H/W	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)
4	402	558	960	1167	164	1331	314	703	1017
2	411	550	961	1181	164	1345	320	693	1013
1	423	543	965	1208	161	1369	328	685	1013
0.5	437	539	976	1241	159	1400	339	676	1015
0.25	446	538	984	1265	158	1422	343	674	1017
0	473	529	1002	1335	152	1487	360	650	1010

Note: H/W=0 represents the reference climate file.

Table 4: *Annual energy budget for heating and cooling in the three test locations, for different street canyon configurations, as predicted by CAT – WITH MUTUAL SHADING, East-West Canyon.*

	Adelaide			**Glasgow**			**Sde Boqer**		
H/W	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)	**heating** (GJ)	**cooling** (GJ)	**total** (GJ)
4	1006	167	1174	1816	24	1840	864	247	1111
2	615	288	903	1411	46	1457	495	398	892
1	534	397	931	1308	89	1397	410	507	917
0.5	489	459	948	1289	116	1405	375	578	953
0.25	470	495	965	1288	131	1419	361	623	984

changes in air temperature only and secondly with the combined effect of air temperature and canyon shading.

Table 3 shows the differences in heating and cooling budgets calculated by EnerWin for Adelaide, Glasgow and Sde Boqer, using air temperature modified by CAT for different canyon aspect ratios but without considering the shading afforded by the canyon on the test building. This case, showing only the effect of the air temperature modifications could be considered representative of all orientations in a typical urban environment. In each location, the predicted heating budget becomes progressively smaller as the street canyon becomes deeper, reflecting the increasing intensity of the nocturnal urban heat island. The effect of modifying air temperature on the predicted heating energy budget in Adelaide has the largest effect, while the effects of the temperature modification in Glasgow are in line (but smaller) with those reported by Watkins et al (2002) for London, which showed a 22% reduction in heating energy budget and a 25% increase in the cooling energy budget. Conversely, the predicted cooling budgets increase in each location. When the building is modelled taking into account the mutual shading for the particular case of an east-west orientated canyon, the effect of the air temperature modification on the energy budgets are shown in Table 4. Here the conclusions we might draw from the general case (Table 3) are reversed emphasising the significant effect that access to solar radiation has on the overall energy performance of a building.

In no case is the effect of the canyon aspect ratio on the predicted annual budget for heating or cooling linear: As Figure 9 shows, increasing the aspect ratio (H/W) beyond a value of about 2 (a narrow street) has only a marginal effect, in all three locations. This is because the exchange of long wave radiation with the atmosphere is affected by the sky view factor, Ψ_s, which for a symmetrical, semi-infinite street canyon is given by

$$\Psi_s = \cos \theta$$

Where. θ. is the angle between the surface and the uppermost edge of the canyon wall.

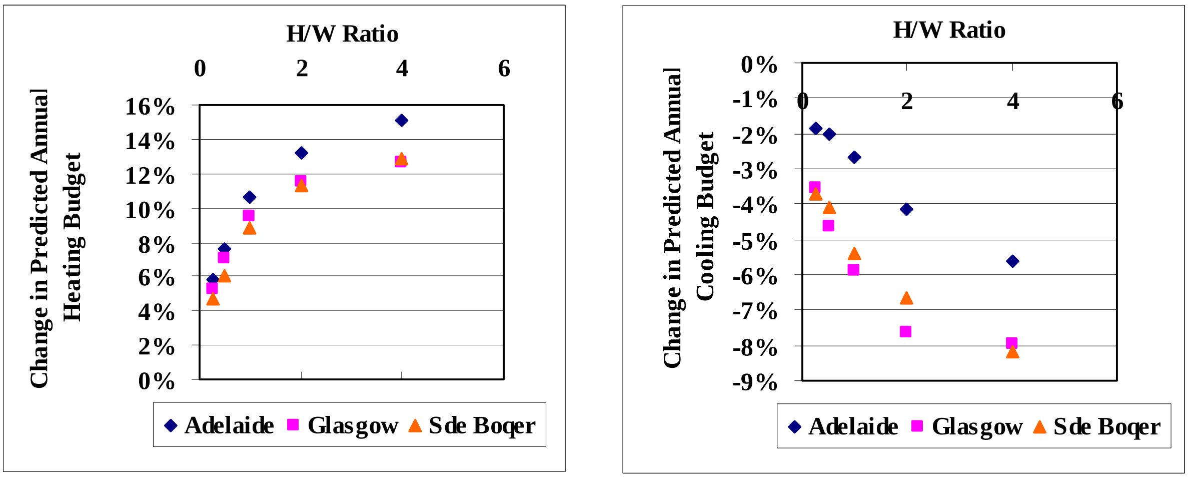

Figure 9: *Error in annual budget for heating the generic office building (left) and cooling it (right), as a result of urban modification of air temperature and NO Mutual SHADING, as predicted by EnerWin for three locations in different climate zones.*

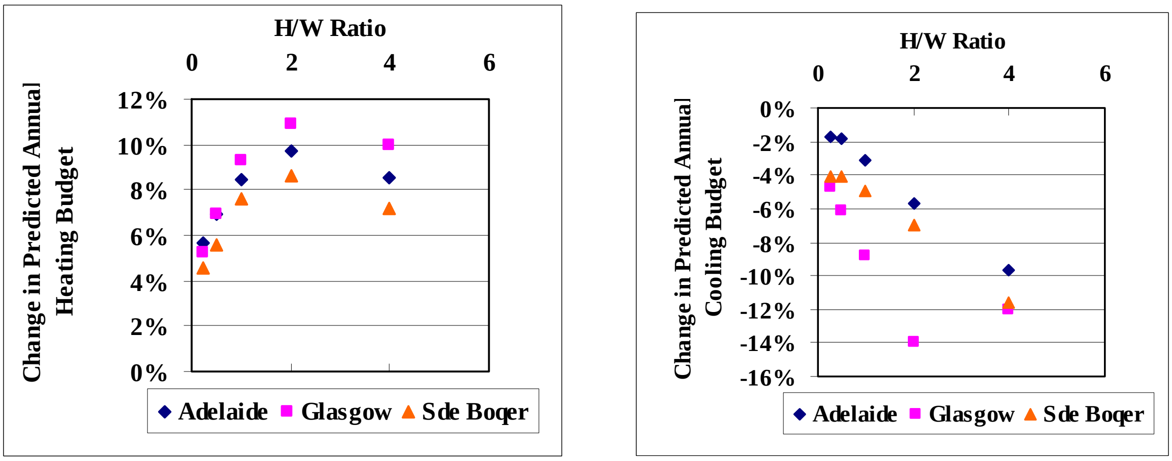

Figure 10: *Error in annual budget for heating the generic office building (left) and cooling it (right), as a result of urban modification of air temperature and WITH mutual SHADING in East-West Canyon, as predicted by EnerWin for three locations in different climate zones.*

DISCUSSION AND CONCLUSION

Urban modification of air temperature is not constant with respect to time, and the differences in temperature between a reference climate data and a particular urban location may vary according to a diurnal and seasonal pattern. Furthermore, although the urban heat island is better known, the city may also experience lower air temperature in certain conditions and at certain times of the year (an urban cool island), as shown by the CAT simulation and as found in several field studies (Steinecke 1999; Runnalls and Oke 2000; Erell and Williamson 2007). As Table 3 shows, although there may be substantial differences in both heating and cooling budgets, the net effect of urban modification in certain locations may be small (Glasgow shows that largest net variation; a 10% reduction). Ultimately the building energy use will however depend on the relative efficiency of the heating and cooling plant.

As Figures 9 & 10 demonstrate the errors introduced into a simulation by not taking into account the urban modification of temperature are likely to be significant. Realistic assessment of the effect of intra-urban variations in air temperature on site-specific energy consumption in buildings therefore requires dynamic building thermal simulation software that employs detailed site specific hourly weather inputs.

The canyon air temperatures modelled by CAT as part of this study are not necessarily those actually found in a location. Variations in anthropogenic heat or non-uniform street geometry, for example, may result in significantly different heat island intensities. However, the conditions specified for comparisons of the different locations were realistic, so tentative conclusions may be drawn with respect to the effect of urban density on air temperature.

Although the relationship between density and intra-urban temperature variations may be quantified with reasonable confidence, it would nonetheless be inappropriate to develop recommendations for urban form solely on this basis. Air temperature is but one factor affecting energy consumption in buildings, and for a particular building proposal may not necessarily be the most important one. A comparison of Tables 3 & 4 illustrates this point. However, it is important that the debate on energy conservation in buildings, in the context of the global effort to reduce carbon emissions, is carried out on the basis of detailed and reliable information.

The CAT model is capable of predicting the effect of urban geometry and materials on the evolution of air temperature in a generic urban street canyon. However, air conditioning loads also include latent heat as well as sensible heat, and are thus affected by the moisture content of air, too. Work is in progress to extend and validate the capabilities of CAT to enable it to predict micro-scale variations in atmospheric humidity that are generated by surface variability.

The comparison of simulated energy consumption for street canyons of different depths and in different climate regions illustrates the capabilities of CAT as a tool in urban planning. The results are not unexpected, and highlight the roles of radiant exchange and urban thermal mass in the development of intra-urban temperature differences. Deep street canyons experience stronger nocturnal heat islands and, conversely, more prominent daytime cool islands, than shallow ones. The intra-urban temperature differences are more pronounced in dry locations, and weakest in high latitude cities, where radiative cooling is weaker and latent heat plays a more dominant role in the surface energy budget.

While the trends illustrated by the simulation with respect to the heating and cooling requirements can also be explained in a qualitative manner, it is the quantitative nature of the results that is important. The ability to predict with confidence both peak loads on HVAC equipment and total annual heat consumption is of great value in the design of HVAC systems and in economic calculations regarding their operation and maintenance. The design of such systems is now carried out routinely using detailed whole-building energy simulation models. As this paper illustrates, failing to account for urban modifications to air temperature may lead to errors that are too large to overlook. HVAC plant may be either over–sized or too small, leading to unnecessary expenditure in the first instance or failure to cope adequately with loads in the latter. Optimisation of life cycle costs of the equipment can only be done if the capital cost is assessed correctly and if running costs are estimated realistically. Finally, certification of the performance of the building within the framework of a building energy-rating scheme, a procedure that is now required by regulatory authorities in many countries, might be affected if local climate modifications are not accounted for. This has policy, legal and financial implications that should certainly not be ignored.

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