Eurographics Workshop on Urban Data Modelling and Visualisation (2014)
V. Tourre and G. Besuievsky (Editors)

Ground temperature modelling: The case study of Rue des Maraîchers in Geneva

G. Upadhyay [1*], J. Kämpf [1] and J-L. Scartezzini [1]

[1] Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
*To whom the correspondence should be addressed. E-mail: govinda.upadhyay@epfl.ch

Abstract

This paper presents a methodology to approximate the urban heat island effect by using a PostgreSQL database and CitySim software, a simulation tool to evaluate urban energy flows. A ground temperature model has been developed for shallow depths (until 4m), which reproduces the phenomena of heat transfer into the ground on an hourly basis. This model is further used to predict the outdoor ground surface temperature, which is an indicator of the urban heat island effect. A PostgreSQL database which contains information such as the building footprints, geographical location, address, construction date, energy system etc. of the buildings was modified to include data relative to this model. A case study has been performed in a small neighbourhood, Rue des Maraîchers, in Geneva (Switzerland) in order to illustrate the usage of this tool to analyse the surface temperature of asphalted roads and green alleys. Finally, a methodology has been introduced to predict the urban heat island effect using this temperature.

1. Introduction

A study by Pfeiffer *et.al* [PKW05] showed that without a significant change of practice, non-retrofitted buildings will represent 80% of the total thermal energy consumption by 2050. This energy waste needs to be addressed by finding adequate means of sustainable energy production, storage and distribution as well as a more efficient energy consumption strategy. It should be noted that the energy demand of a city highly depends on the microclimate around its buildings and on the urban heat island effect [BBA07, OJSW91, SPL*01]. The waste heat from buildings, industries and transportation further contribute to this effect. Computer simulation and modelling at building and urban scale provides a better insight to urban planners and designers to deal with this situation. However, most of the tools available on the market predicts only building energy demand and lacks microclimate simulation [RCG07, TRN13, KSS10, Ene13]. Furthermore, urban energy simulation tools such as CitySim [Rob11], require a significant amount of data which is difficult to handle compared to individual building simulation models. Further, the tools available such as ENVI-net [Bru11], TEST [AHN08], to determine the microclimate outside, neglects the dynamic of the indoor effects which might have strong influence on the wall temperature. This effect is taken into consideration in CitySim while calculating the outer surface temperatures. CitySim contains a radiation model based on Perez All Weather and Simplified Radiosity algorithm [RS05] which used to compute the hourly irradiation on the building surfaces direct from the sun, diffuse from the sky and reflected by other surfaces.

This paper presents the modification of a database model for urban energy simulation using PostgreSQL, a converter which creates an input XML file for CitySim using the database and used to determine the outdoor ground surface temperature of a small neighbourhood (Rue des Maraîchers) in Geneva in order to provide an indication of the urban heat island effect. A 3D graphical representation of the ground temperatures is further introduced to highlight their gradient inside an urban canyon.

2. Methodology

Database management systems (DBMS) and geographical information systems (GIS) provide excellent tools for data handling, and can be integrated within simulation modules [Gut94, Sui98]. Their modeling capabilities are limited, but

DOI: 10.2312/udmv.20141072

their usage for urban energy simulation programs is very effective [PKW11]. PostgreSQL is a complete and open-source DBMS, offering a wide range of conventional SQL functionalities for data handling. It also uses the spatial data module PostGIS, which provides geometrical data types (such as points, lines, polygons and collections of these) as well as a multitude of related functions to access, edit and process spatial data. The open source GIS software QuantumGIS [QGI13] has been used to access, visualise and modify data in a PostgreSQL database, and to produce map representations of any parameter linked with the building geometry. Building footprints were added in the database using cadastral maps, which follow a 2D representation. This information is completed with the average height and altitude of the buildings. The database also contains information such as the geographical location, address, construction date, energy system etc. of the buildings.

There are many advantages to DBMS: 1) disparate original source files (.shp for maps, .dbf etc.) can be loaded as temporary databases in form of simple tables, 2) a data model can be used as a link between the specific input file of CitySim and the main data source and 3) SQL and spatial functions can be used to combine the different data sources, based on the common identifiers such as the building ID or the spatial location.

The methodology described by Perez [DR11] has been used to evaluate ground surface temperature in a small neighbourhood in Geneva, which gives an indication of the urban heat island effect. A converter based on programming language has been written to retrieve data stored in the database, transform it into the input format of CitySim and run the simulation. This program is also used to insert the output results obtained from CitySim into the database. For each building, the 2D geometrical footprint is used to develop a 2.5D representation based on the altitude and average height of each building. Furthermore, the common surfaces among buildings are considered adiabatic as the thermal losses or gains are usually negligible between the attached buildings. Each building surface (wall, roof or floor) is then described by a construction wall type or a U-value, a glazing ratio and physical properties, as well as a reflectance. The same method is used for the ground surfaces. The converter then launches a CitySim simulation using the input file and an hourly climatic data file produced by Meteonorm [Met13]. Figure 1 shows the execution sequence to get a CitySim simulation based on the information retrieved from the database.

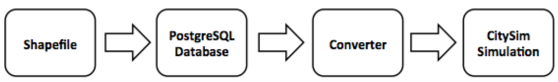


Figure 1: *Methodology used for simulation with CitySim using Shape file.*

3. Ground modelling with CitySim

The ground surface temperature can provide an indication of the local air temperature [SK04] which is important for the study of the microclimate effect at urban scale. Generally, an approximation is done where the ground temperature is taken as the thin air layer temperature (sol-Air temperature) [Mac44]. This ignores the heat transfer conductance inside the ground which may leads to ill-calculation of the surface temperatures. Moreover, existing ground models assumes single layer ground surface to calculate the temperature, which is not the case in reality [CN98]. A study by Florides *et.al* [FK07] showed that the ground temperature at the shallow depth (1-4 m) is influenced significantly by the daily weather condition.

A ground temperature model has been developed and implemented in CitySim for shallow depth (until 4m) which reproduces the phenomena of heat transfer into the ground on an hourly basis. A simplified model has been developed, considering the ground conductivity, layer depths and thermal capacitance. The physical formulation of the different layers is being modelled as an electrical network of resistances and capacitances. This ground model can be used to analyze the surface ground temperature as well as the temperature into the ground. A 4 layer (asphalt, gravel, sand, molasses soil) road surface is shown in Figure 2 as an electrical equivalent network for the different layers and Kirchoff's current law at each nodes has been used to determine the desired temperatures [Kae09]. Equation 1, 2 represents the heat flow in the layer 1. Similar set of differential equations are written for all the layers with the boundary and initial conditions and solved to obtained the ground temperature.

$$C_1.\frac{dT_1}{dt} = (-\kappa_1 - \kappa_2).T_1 + \kappa_1.T_{air} + w_w.Q_{sun} \quad (1)$$

$$\kappa_1(t) = \frac{g_1.g_e(t)}{g_1 + g_e(t)}, \kappa_2 = \frac{g_1.g_2}{g_1 + g_2} \quad (2)$$

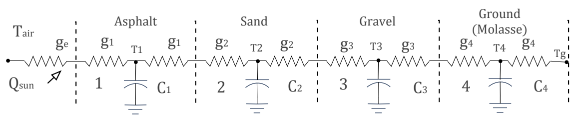


Figure 2: *RC circuit representation of the ground. g represents conductivity, C represents capacitance, T represents temperature at various layer.*

As boundary condition for ground temperature (T_g), the Kasuda model [KA65] has been used, which predicts the ground temperature at any depth (z m) as shown in Equation 3.

$$T_g = \bar{t} - \tilde{t}.exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right).cos\left(\frac{2\pi}{365}\cdot\left(d - d' - \frac{z}{2}\sqrt{\frac{365}{\pi.\alpha}}\right)\right) \quad (3)$$

where, $\bar{t}$ is the annual mean temperature (°C), $\tilde{t}$ is the amplitude in mean daily temperature swing (°C), α is the soil diffusivity (m^2/day), d is the day and d' is the day at which a minimum mean daily temperature occurred.

A database was modified to incorporate the data required for ground modelling such as the ground materials and their thermal properties. Figure 3 represents a schematic of the tables in the database including the *ground* table. The *building* table is related to *walltype* which is further linked to a *material* table via a *layer* table. Similarly, the ground table has been added and linked to groundtype; it is connected to the material table via a ground layer. Further, an output table has been set up in the database in order to store the ground surface temperature, and facilitate the analysis of the results for a large number of ground surfaces.

4. Case Study: Rue des Maraîchers, Geneva

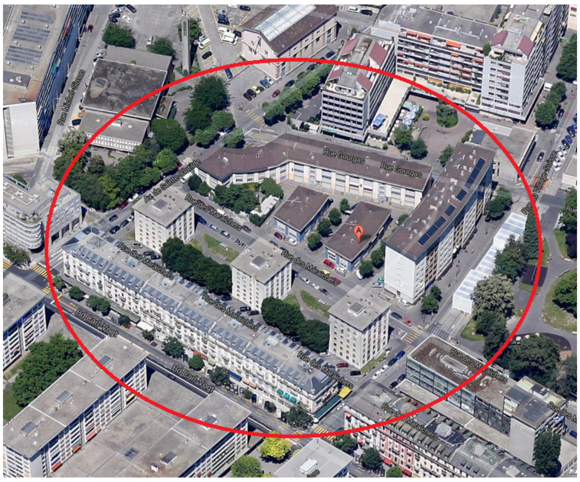
A case study was performed on a neighbourhood, Rue des Maraîchers in Geneva (Figure 4(a)), to determine the ground surface temperature in order to provide an estimation of the urban heat island effect. The studied area consists of 8 buildings, 3 green alleys (with trees) and an asphalted road (Figure 4(b)). The main objective of the case study was to analyse the surface temperature of the roads.

The building footprints were imported to the database without the ground surface; the ground surfaces were added using QuantumGIS 1.8.0 software, which updated the ground table database with the thermal properties and their geometric location. CitySim simulations were performed to see the effect of asphalted roads and the green areas on the surface temperature.

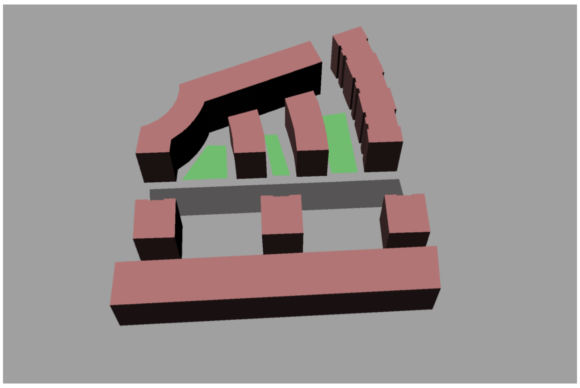
Material	Conductivity (W/m.K)	Specific heat (kJ/kg.K)	Density (kg/m^3)	Layer Thickness (cm)
Asphalt	0.75	920	2360	2.5
Sand	0.5	828	1300	2.0
Gravel	0.7	792	1800	10
Clay	0.97	920	1760	2.5
Loam	1.4	864	1800	10
Sand	0.5	828	1300	2.0
Moraine (Soil)	2.4	1200	1600	85

Table 1: *Road (Asphalt) ground and green surface material properties [Mat11].*

Asphalted roads were modelled as asphalt, sand and gravel; green surfaces as clay, loam and sand. The material table in the database was updated with the corresponding thermal properties. The material properties are given in Table 1. Moraine soil has been used as foundation soil for 1 m depth [SIT, GF13]. Furthermore, shortwave reflectance assuming perfectly diffusive surfaces, of 0.14 and 0.21, has been used for the upper layer of asphalted and green roads, respectively [Bem13].



(a)



(b)

Figure 4: *Locality view (a) Satellite image (b) 3D model used for the simulation: Green surface are the green ground, grey surface is the asphalted road, brown surfaces are the building.*

4.1. Simulation Results

Figure 5 represents the surface temperature of the asphalt and green roads for winter and summer time. It also shows the temperature difference between the two surfaces for a whole year. All the green areas showed a similar temperature profile, hence only one green surface temperature profile has been used in the analysis. It can be seen that the maximum

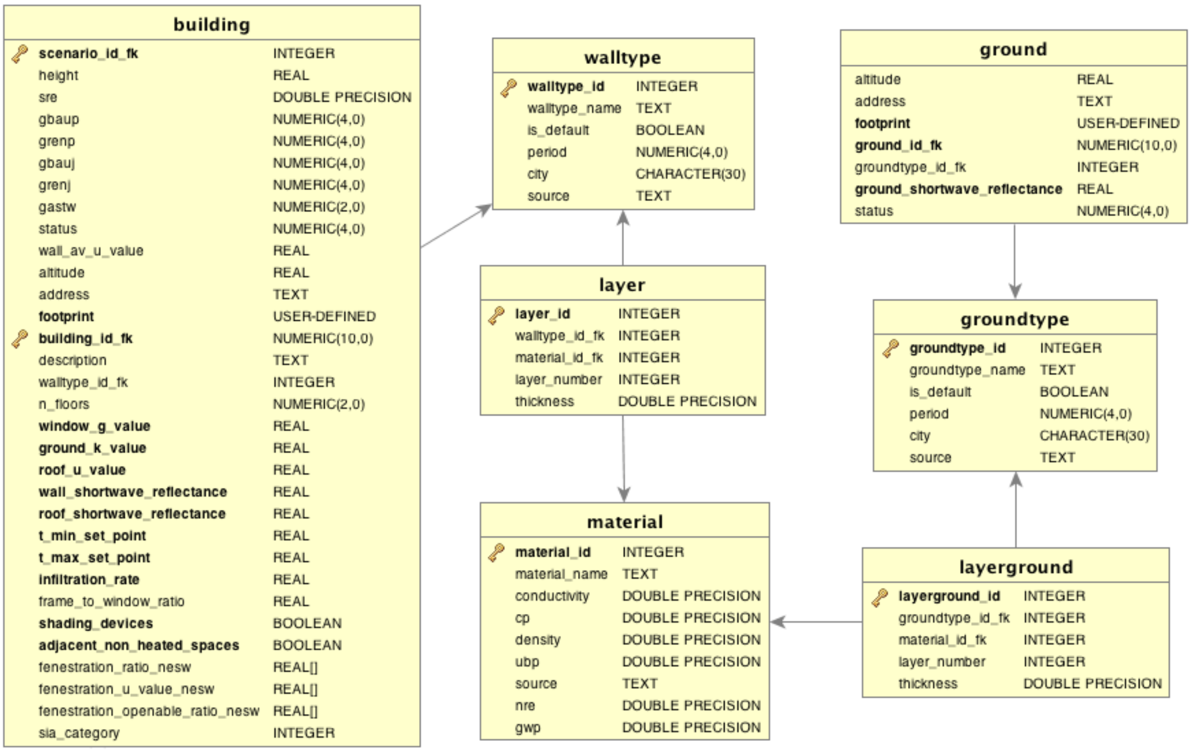


Figure 3: *Geneva database schematic*

surface temperature difference is 20°C. This can have a significant impact on human comfort [Fan70]. A snapshot of the simulation is being presented using CitySim Designer (GUI) as shown in Figure 6. Here, the surfaces are further divided into small grids (1m^2) to detect the hot spots on the surfaces to understand the distribution of the surface temperature. It can be noticed that the surfaces closer to the buildings are at lower temperature which could be due to the shadowing effect. Furthermore, the figures shows that the asphalted surface has a higher average temperature than the green one. Hence, this tool can be used to design green quarters and select adequate materials for the outdoor surfaces in order to mitigate the surface temperatures in summer. It should be noted that there are no significant differences in thermal properties between the layers in the studied cases; the thickness of the different layers of both has been assumed to be similar, due to the lack of field data. Furthermore, the evapotranspiration phenomenon has been ignored; it will be added in the future. Also, field data will be obtained to validate these results.

5. Future monitoring: Urban heat island effect

CitySim provides external surface temperatures which can be used to determine the amount of heat released in the atmosphere under low wind condition. For evaluating the urban heat island effect, it is important to estimate the maximum heat trapped in the volume under consideration. This heat is not only important for the human outdoor comfort, it can also increase the building energy demand for cooling [BBA07, OJSW91, SPL*01]. The trapped heat can be calculated using Equation 4, 5.

$$Q_{released} = \sum_{i=allsurfaces} h_c.S_i.(T_s - T_a) \quad (4)$$

$$T_{released} = \frac{Q_{released}}{\rho_{air}.V_{air}.C_p} \quad (5)$$

where, $Q_{released}$(Wh) is the total heat released, h_c is convective heat coefficient of the thin air layer (25 W/(m^2.K)) under low wind condition (approx.1 m/s [ILD11], S_i (m^2) is the outdoor surface area, T_s (°C) is the outdoor surface temperature, T_a (°C) is the external air temperature, $T_{released}$ (°C) is the temperature expected in the area due to the heat

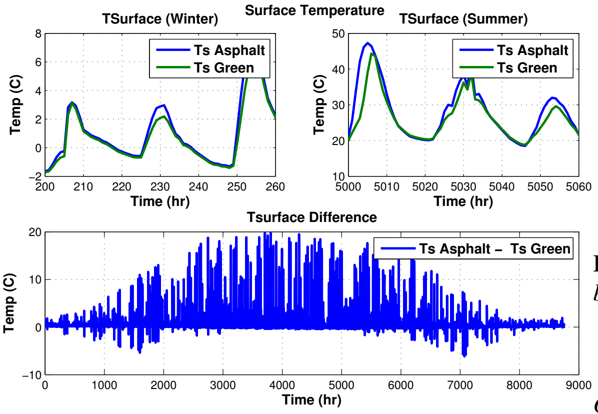


Figure 5: *Surface temperature comparing green (Ts Green) and asphalted (Ts Asphalt) surface. Top: A winter case and summer case have been presented. Bottom: surface temperature difference for the whole year.*

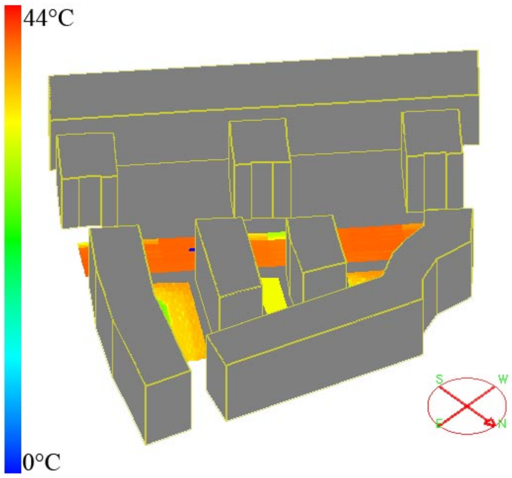


Figure 6: *A snapshot of the road surface temperature of Rue des Maraîchers in Geneva. A temperature gradient can be seen on the surfaces.*

released, V_{air} (m^3) is the air volume in the area (V_{air} = $Area_{ground}$. $height_{building}$), ρ_{air} (kg/m^3) is the air density and C_p (J/ (kg.K)) is the heat capacitance of the air.

As shown in Figure 7, the following equations can be used to estimate the urban heat island temperature in street canyons.

$$Q_{released} = Q_{1\rightarrow a} + Q_{2\rightarrow a} + Q_{3\rightarrow a} \quad (6)$$

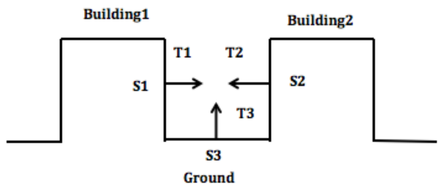


Figure 7: *Street canyon showing two buildings and a ground between them.*

$$Q_{released} = h_c.S_1.(T_1 - T_a) + h_c.S_2.(T_1 - T_a) + h_c.S_3.(T_3 - T_a) \quad (7)$$

Furthermore, the average air temperature in the street canyon can be calculated using Equation 5. This approach will be used in CitySim to evaluate urban heat island evolutions in the future.

6. Conclusion

The methodology used in this work simplifies and accelerates significantly urban scale simulation process with CitySim based on a database management system (DBMS) PostgreSQL. A converter, written in Java programming language, is being used to retrieve the data from the database, create input XML for CitySim, launch a simulation and insert the results into the database. Furthermore, this work discusses the ground modelling which adds another dimension to the urban simulation where not only energy flows but also outdoor surface temperatures can be estimated. A case study in Geneva at Rue des Maraîchers was performed to analyse temperature difference between asphalted roads and green alleys with trees. The maximum surface temperature difference observed was 20°C which can have a significant impact on human comfort. And, a methodology will be used to approach the urban heat island effect using CitySim software.

References

[AHN08] Asawa T., Hoyano A., Nakaohkubo K.: Thermal design tool for outdoor spaces based on heat balance simulation using a 3D-CAD system. *Building and Environment* (2008). URL: http://www.sciencedirect.com/science/article/pii/S036013230700251X. 1

[BBA07] Bozonnet E., Belarbi R., Allard F.: Thermal behaviour of buildings: modelling the impact of urban heat island. *Journal of Harbin Institute of Technology* (2007). URL: http://hal.archives-ouvertes.fr/hal-00312181/. 1, 4

[Bem13] Bembook: Reflectance data, 2013. URL: http://www.bembook.ibpsa.us/index.php?title=Ground_Reflectance. 3

[Bru11] Bruse M.: ENVI- met : Three - dimensional microclimate model, 2011. URL: http://www.envi-met.com/. 1

[CN98] CAMPBELL G. S., NORMAN J. M.: *An Introduction to Environmental Biophysics*. Springer New York, New York, NY, 1998. URL: http://link.springer.com/10.1007/978-1-4612-1626-1, doi:10.1007/978-1-4612-1626-1. 2

[DR11] D. PEREZ, J. H. KÄMPF, U. WILKE M. P., ROBINSON. D.: CITYSIM simulation: the case study of Alt-Wiedikon, a neighbourhood of Zürich City. In *CISBAT* (2011). 2

[Ene13] ENERGYPLUS: Energy simulation software, 2013. 1

[Fan70] FANGER P.: *Thermal comfort. Analysis and applications in environmental engineering.* 1970. URL: http://www.cabdirect.org/abstracts/19722700268.html. 4

[FK07] FLORIDES G., KALOGIROU S.: Ground heat exchangers - A review of systems, models and applications. *Renewable Energy 32*, 15 (Dec. 2007), 2461–2478. URL: http://linkinghub.elsevier.com/retrieve/pii/S0960148107000092, doi:10.1016/j.renene.2006.12.014. 2

[GF13] GRAF F., FREI M.: Soil aggregation and slope stability related to soil density, root length, and mycorrhiza. *EGU General Assembly Conference Abstracts* (2013). URL: http://adsabs.harvard.edu/abs/2013EGUGA..15.1832G. 3

[Gut94] GUTING R.: An introduction to spatial database systems. *Spatial Database Systems, VLDB 3*, 4 (1994). URL: http://dl.acm.org/citation.cfm?id=615206. 1

[ILD11] INCROPERA F., LAVINE A., DEWITT D.: *Fundamentals of heat and mass transfer.* 2011. URL: http://books.google.com/books?hl=en&lr=&id=vvyIoXEywMoC&oi=fnd&pg=PR21&dq=Fundamentals+of+Heat+and+Mass+Transfer&ots=8HwlMReZGb&sig=wXkA_5ZDCOzKHNmjzG1LVEeCh2A. 4

[KA65] KUSUDA T., ACHENBACH P.: Earth temperature and thermal diffusivity at selected stations in the United States. *ASHRAE Transactions 71*, 1 (1965). URL: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0472916. 2

[Kae09] KAEMPF J.: *On the modelling and optimisation of urban energy fluxes*. Phd, EPFL, Lausanne, 2009. URL: http://biblion.epfl.ch/EPFL/theses/2009/4548/4548_abs.pdf. 2

[KSS10] KEIRSTEAD J., SAMSATLI N., SHAH N.: SynCity: an integrated tool kit for urban energy systems modelling. *Energy Efficient Cities* (2010). URL: https://workspace.imperial.ac.uk/urbanenergysystems/public/urs_keirstead2009.pdf. 1

[Mac44] MACKEY C.: Sol-air temperature: new concept. *Heat. Vent.;() 41*, 12 (1944). URL: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5052685. 2

[Mat11] MATWEB L.: Material Database, 2011. URL: http://www.matweb.com/. 3

[Met13] METEONORM: Meteonorm : http://meteonorm.com/, 2013. URL: http://meteonorm.com/. 2

[OJSW91] OKE T., JOHNSON G., STEYN D., WATSON I.: Simulation of surface urban heat islands under 'ideal'conditions at night Part 2: Diagnosis of causation. *Boundary-Layer Meteorology* (1991), 339–358. URL: http://link.springer.com/article/10.1007/BF00119211. 1, 4

[PKW05] PFEIFFER A., KOSCHENZ M., WOKAUN A.: Energy and building technology for the 2000W society - Potential of residential buildings in Switzerland. *Energy and Buildings 37*, 11 (Nov. 2005), 1158–1174. URL: http://linkinghub.elsevier.com/retrieve/pii/S037877880500109X, doi:10.1016/j.enbuild.2005.06.018. 1

[PKW11] PEREZ D., KÄMPF J., WILKE U.: CITYSIM simulation: the case study of Alt-Wiedikon, a neighbourhood of Zürich City. *Proceedings of CISBAT 2011 - CleanTech for Sustainable Buildings* (2011), 937–940. URL: http://infoscience.epfl.ch/record/174435. 1

[QGI13] QGIS: A Free and Open Source Geographic Information System, 2013. URL: http://www.qgis.org/en/site/. 2

[RCG07] ROBINSON D., CAMPBELL N., GAISER W.: SUNtool - A new modelling paradigm for simulating and optimising urban sustainability. *Solar Energy* (2007). URL: http://www.sciencedirect.com/science/article/pii/S0038092X0700120X. 1

[Rob11] ROBINSON D.: *Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications*. 2011. URL: http://dl.acm.org/citation.cfm?id=2011849. 1

[RS05] ROBINSON D., STONE A.: A simplified radiosity algorithm for general urban radiation exchange. *Building Services Engineering Research Technology* (2005). URL: http://bse.sagepub.com/content/26/4/271.short. 1

[SIT] SITG: Le système d'information du territoire à Genève (SITG) http://ge.ch/geoportail/pro/. URL: http://ge.ch/geoportail/pro/. 3

[SK04] SIGNORELLI S., KOHL T.: Regional ground surface temperature mapping from meteorological data. *Global and Planetary Change 40*, 3-4 (Feb. 2004), 267–284. URL: http://linkinghub.elsevier.com/retrieve/pii/S0921818103001449, doi:10.1016/j.gloplacha.2003.08.003. 2

[SPL*01] SANTAMOURIS M., PAPANIKOLAOU N., LIVADA I., KORONAKIS I., GEORGAKIS C., ARGIRIOU A., ASSIMAKOPOULOS D.: On the impact of urban climate on the energy consumption of buildings. *Solar Energy 70*, 3 (Jan. 2001), 201–216. URL: http://linkinghub.elsevier.com/retrieve/pii/S0038092X00000955, doi:10.1016/S0038-092X(00)00095-5. 1, 4

[Sui98] SUI D. Z.: Review Article GIS-based urban modelling : practices , problems , and prospects. *International Journal of geographical information science 12*, 7 (1998), 651–671. URL: http://www.unc.edu/~liangj/geog192/sui.pdf. 1

[TRN13] TRNSYS: Energy simulation software, 2013. URL: http://sel.me.wisc.edu/trnsys/. 1