On the Impact of Local Climatic Conditions on Urban Energy Use: A Case Study

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ABSTRACT:
In this paper we propose to evaluate the microclimatic characteristics of a neighbourhood located in the city of Nablus (Palestine) and study how the wind impacts the energy demand for heating and cooling the buildings.

The present paper proposes a methodology to couple a Canopy Interface Model (CIM) with the software CitySim. CIM provides high resolution vertical profiles of various meteorological parameters (wind speed, temperature and turbulent kinetic energy) while taking into account the vertical distribution of buildings as well as the density of different neighbourhoods. In order to measure the benefits of such a coupling, the results obtained with this methodology are compared back with the regular use of climatic conditions, showing how the prevailing winds flow inside the urban canyons and detailing their impact on the energy demand of buildings during the different periods of a year.

The results from this study indicate that urban planning has a significant influence on the local meteorological conditions in highly dense areas. This in turn impacts the energy demand of the buildings via two main variables: the access to solar gains and the local estimated convective heat transfer coefficients. This paper initiates possible interesting studies that will be carried out in the future to determine with more precision how the proper modelling of these two variables can help in designing more sustainable neighbourhoods taking into account local climatic conditions.

Keywords: Building energy consumption, urban micro-climate, energy simulation

INTRODUCTION

The recent report by the Intergovernmental Panel on Climate Change (IPCC, 2013) highlighted the need to decrease our greenhouse gas emissions in order to mitigate the current climate change. Buildings are one of the major sources of energy consumption and GHG emissions (ADEME, 2012); there is therefore a huge potential to decrease their energy use. Furthermore, the thermal comfort of inhabitants in cities will become more and more impacted with the increase in heat waves predicted by the IPCC (2013). It is thus essential to build more sustainable and liveable urban areas.

It is now well known that building energy demand and urban climate are closely related and interdependent (Ashie et al., 1999; Salamanca et al., 2011). Historically, neighbourhoods have been built based on the local climate, taking advantage of local prevailing conditions; newer neighbourhoods with larger street / building ratio, however are mostly built without such considerations and the meteorological conditions in their outdoor areas are often not very comfortable for the inhabitants, particularly for hot dry climate (Ali-Toudert and Mayer, 2006; Johansson, 2006). Furthermore, buildings consume more and more energy to improve the indoor thermal comfort while neglecting the release of anthropogenic heat and associated greenhouse gases.

The calculation of building energy use is a tedious task as it needs to account for complex non-linear phenomena. Several computational software have hence been developed to estimate the energy use in buildings. CitySim (Kämpf and Robinson, 2007; Robinson, 2012), for example, allows the quantification of the heating and cooling demand of buildings at the urban scale. Traditionally, these energy demand software, such as EnergyPlus (Crawley et al., 2000) or CitySim use data coming from a meteorological station located outside the city. These data often miss to represent the effects of buildings on the local meteorological variables (wind or temperature).

A Canopy Interface Model (CIM) was developed (Mauree, 2014) with the purpose of enhancing the representation of buildings in meteorological software to better calculate their impact on various variables. In recent studies, the ability to couple the two software CIM and CitySim was demonstrated (Mauree et al., 2015a, 2015b).

We propose here to evaluate the impact of the coupling of these two models. Instead of applying uniformly the wind characteristics (speed and direction) monitored at a meteorological station (provided, for example, by the software Meteonorm), the simulation will be using the local climatic conditions prevailing around the buildings. These variables are then used to compute a convective heat transfer coefficient used by the software CitySim to assess the energy demand.

This paper is divided as follows. We first present briefly CIM and CitySim. We then describe the study case and the characteristics of the building in the area. The section that follows, give the results and discuss the impact of using the local meteorological data. Finally we conclude and give a few perspectives to this work.

METHODOLOGY

Canopy Interface Model

A one-dimensional Canopy Interface Model was recently developed (Mauree, 2014) to improve the surface representation in mesoscale meteorological models and to also prepare the coupling with microscale models.

CIM uses a 1-D diffusion equation derived from the Navier-Stokes equations. EQUATION 1 is used to calculate the wind speed ($m \cdot s^{-1}$) in both directions (we only show the equation for one direction) while EQUATION 2 is used for the calculation of the potential temperature (K):

$$\frac{\partial U}{\partial t} = \frac{\partial}{dz}\left(\mu_t \frac{\partial U}{\partial z}\right) + f_u^s \qquad (1)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{dz}\left(\kappa_t \frac{\partial \theta}{\partial z}\right) + f_\theta^s \qquad (2)$$

where U is the horizontal wind speed in either the x- or y-direction, θ is the potential temperature, μ_t is the momentum turbulent diffusion coefficient, κ_t is the heat turbulent diffusion coefficient and f_u^s and f_θ^s are the source terms representing the fluxes (from the surface or buildings) that will impact the flow.

The momentum diffusion coefficient is calculated using:

$$\mu_t = C_\mu \sqrt{E} l \qquad (3)$$

$$\kappa_t = \frac{C_\mu \sqrt{E} l}{Pr} \qquad (4)$$

where C_μ is a constant equal to 0.3 and E is the turbulent kinetic energy (TKE). l is defined as the mixing length and is taken from Santiago and Martilli (2010). The mixing length is calculated as:

$$l = \max(h - d, z - d) \qquad (5)$$

where d is the displacement height calculated using:

$$d = h(1 - \phi)^{0.13} \qquad (6)$$

and where h is the height of buildings, ϕ is the volume porosity, 0.13 is a constant from Santiago and Martilli (2010). This formula has been adapted to account for the obstacles density and varying building height in the canopy.

CitySim

CitySim is a large-scale dynamic building energy simulation tool developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). The tool includes an important aspect in the field of many buildings simulation: the building interactions (shadowing, light inter-reflections and infrared exchanges). Furthermore, CitySim is based on simplified modelling assumptions to establish a trade-off between input data needs, output precision requirements and computing time.

In this study, CitySim calculates a convection heat transfer coefficient (Mirsadeghi et al., 2013) that will take into account the local wind speed. More information on the coupling between CIM and CitySim can be found in Mauree et al., (2015a, 2015b).

STUDY CASE

The old city of Nablus is composed of six districts hosting residential and commercial functions; between them the residential Al-Habaleh district (also called Haret El-Hablleh) was selected as case study (see Figure *1*).

Figure 1: Old city of Nablus, with the six districts: Al-Gharb, Al-Yasmeneh, Al- Qaryon, Al Aqabeh, Al-Qaisaryyeh and Al-Habaleh (red rectangle).

The buildings of the old town are built with local limestone (Yousof, 1989) with typical white, yellowish and greyish colours; the thickness of the envelope in traditional houses varies between 80-120 centimetres. The walls are composed of three layers: two external layer of stone and an internal layer filled with mortar and stone rubble (Table 1); the glazing ratio is retrieved by the plans of a courtyard house in the Old city (Al-Amad, 1998) and is assumed equal to 0.1, considering the average between the walls facing the street (with a low glazing ratio) and walls facing the internal courtyard, with a superior glazing ratio. Flat roof are traditionally composed of one layer of stone tiles, covered by mud earth, and supported by a wooden structure (Salameh, n.d.). The glazing U-value corresponds to 2.7 $W{\cdot}m^{-2}K^{-1}$ (considering the glazing and the frame) and the g-value to 0.7.

Table 1: Traditional walls. Thermophysical parameters: Density, Specific Heat, Thermal Conductivity and Thickness.

Name	Density ρ ($kg{\cdot}m^{-3}$)	Specific Heat *c* ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)	Thermal Conductivity κ ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	Thickness (m)
Limestone	2000	1000	1.4	0.35
Mortar and stone rubble	2000	1050	2	0.15
Limestone	2000	1000	1.4	0.30

Equivalent geometry
As opposed to CitySim, where the actual geometry of the buildings in the study cases is described (see Fig. Figure 2), we defined an equivalent geometry (see Fig. Figure 3 and Table 2) for CIM.

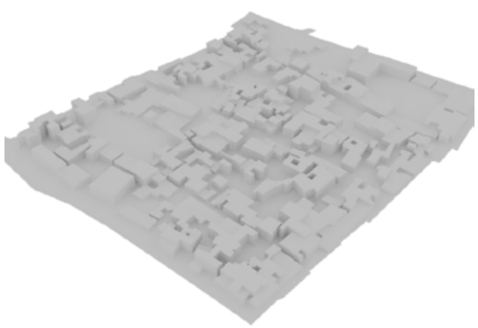

Figure 2: 3D view of the geometry used in CitySim for the considered neighbourhood.

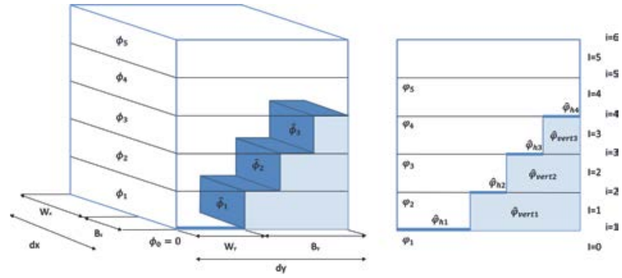

Figure 3: Equivalent geometry used in CIM for the considered neighbourhood (left 3D view and right front view of the neighbourhood).

We considered the neighbourhood to be composed of homogeneous obstacles. As shown in Table 2, we defined buildings, as squared elements piled on each other but having different sizes to account for the different building heights. The tallest building in the domain has 4 floors, with each level in the CIM having a vertical resolution of 3m.

CIM is forced using the data from Meteonorm for Nablus. It then computes new boundary conditions (wind speed, wind direction and air temperature) for CitySim by calculating their average in the urban canopy.

The heating and cooling demand is calculated by the software CitySim, considering the energy required to maintain an internal temperature between 20 to 26°C.

Table 2: Building geometrical characteristics.

Level	*Bx/By*	*Wx/Wy*
1	323	177
2	230	270
3	116	384
4	33	467

RESULTS

The energy demand of the site varies drastically with the new weather data provided by the CIM model: the heating demand increases by 9%, passing from 87 $kWh{\cdot}m^{-2}$ to 97 $kWh{\cdot}m^{-2}$, on the contrary the cooling demand is completely reduced, passing from 12 kWh/m^2 in the base case study, to 3 $kWh{\cdot}m^{-2}$ in the new model. Figures 4 to 7 show the heating and cooling demand of the old city, as function of the weather data provided by Meteonorm and CIM.

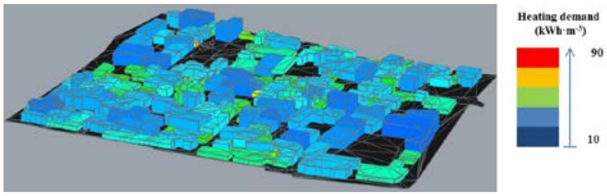

Figure 4: 3D view of the heating demand of the site, by using the weather data provided by Meteonorm. Maximal heating demand corresponds to 69 kWh·m^{-3}, minimal hating demand corresponds to 14 kWh·m^{-3}.

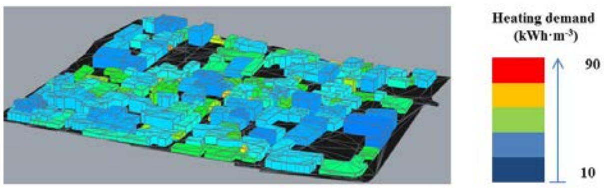

Figure 5: 3D view of the heating demand of the site, by using the weather data provided by CIM. Maximal heating demand corresponds to 84 kWh·m^{-3}, minimal heating demand corresponds to 16 kWh·m^{-3}.

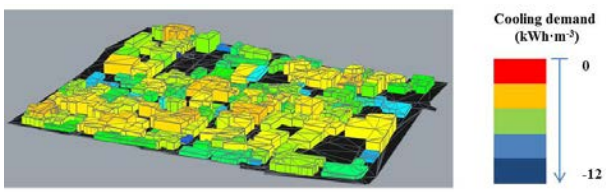

Figure 6: 3D view of the cooling demand of the site, by using the weather data provided by Meteonorm. Maximal cooling demand corresponds to 11 kWh·m^{-3}.

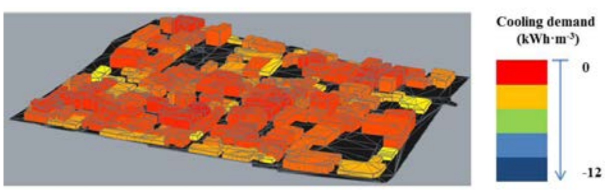

Figure 7: 3D view of the cooling demand of the site, by using the weather data provided by CIM. Maximal cooling demand corresponds to 2 kWh·m^{-3}.

The variation between both models is expressed in Figure 8, where the heating demand (x-axes) is expressed as function of the cooling demand (y-axes): in the simulation realized with Meteonorm weather data solely, the heating demand varies between 1.4 MWh to 159 MWh; on the contrary coupled with the CIM simulation, the heating demand varies between 1.5 MWh to 172 MWh. The cooling demand of buildings with the CIM is in fact low, with the highest value at 2.8 MWh; on the contrary with the Meteonorm weather data the maximal cooling demand corresponds to 8.8 MWh.

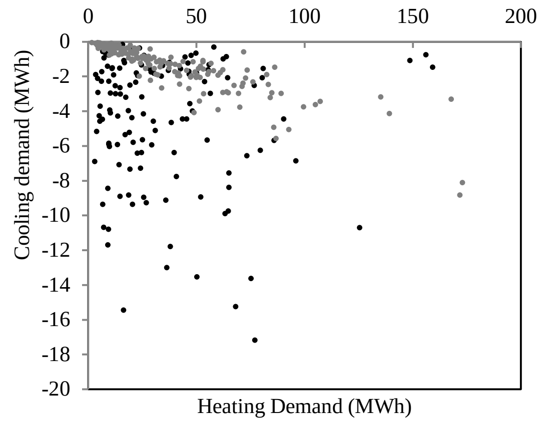

Figure 8: Heating and cooling demand (MWh) of the site, analysed with the software CitySim by using the weather data provided by Meteonorm (black dots) and by CIM (grey dots).

The buildings mostly influenced by the variation in the meteorological data are the ones presenting the highest Form Factor (the ratio between the external envelope and the gross area of the building), because they are more exposed to the variations of the outdoor environment. As an example, a building with one single floor of 21 m² and detached by neighbouring buildings (so called Building A), presents a heating demand of 228 kWh·m^{-2} with the Meteonorm weather data, and a heating demand of 256 kWh·m^{-2} (+11%) with the weather data provided by CIM; the cooling demand passes from 19 kWh·m^{-2} to 3 kWh·m^{-2} respectively.

The obtained differences are related to the new local climatic data. When comparing the air temperature from Meteonorm and CIM an average reduction of the air temperature of 2.1°C during the year is noted and the averaged wind speed is reduced from 2.6 m·s^{-1} to 0.7 m·s^{-1}. Additionally, the air temperature decrease is more significant during the summer time (Figure 9) as compared to the winter time.

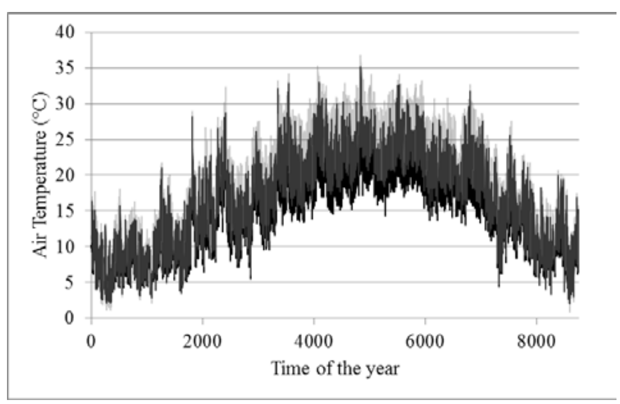

Figure 9: Air temperature (°C) calculated by the software Meteonorm (grey line) and by CIM (black line).

Figure 10a shows four summer days (27th July to 30th July) when the average temperature difference corresponds to 4°C, and is higher during the daytime compared to the nighttime. On the contrary, during the winter time (8th February to 11th February – Fig. 10 b), the daily difference in air temperature corresponds to 0.8°C, and is higher during the daytime (around 1°C) than during the night-time (less than 0.5°C).

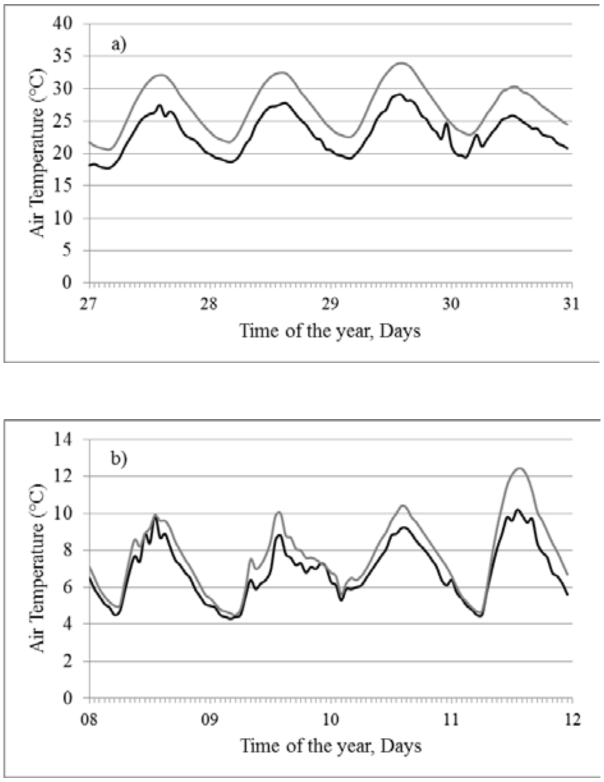

Figure 10: Hourly profile of the air temperature, during four summer day (a) and during three winter days (b). Temperature provided by Meteonorm (grey line) and by CIM (black line).

CIM considers the surface temperature and the stability of the atmosphere when calculating the wind and temperature profiles. Depending on the surface temperatures, the stability of the air parcel in the street canyons can change and this can hence modify significantly the wind profiles in the canopy. Figure 11a shows the wind speed for a case where the atmosphere is considered to be stable with the surface temperature being at 20.7°C and the air temperature at 24.3°C. Figure 11b on the other hand gives an example of a more unstable atmosphere with a surface temperature of 19.4°C and an air temperature at 18.3°C. In the case of the unstable atmosphere, the turbulent fluxes are more important and hence the mixing makes the canopy layer more homogeneous as opposed to the stable case. The stable case, mostly occurring at night, can cause the air temperature to increase locally and temporarily (see spikes in Fig. 10a).

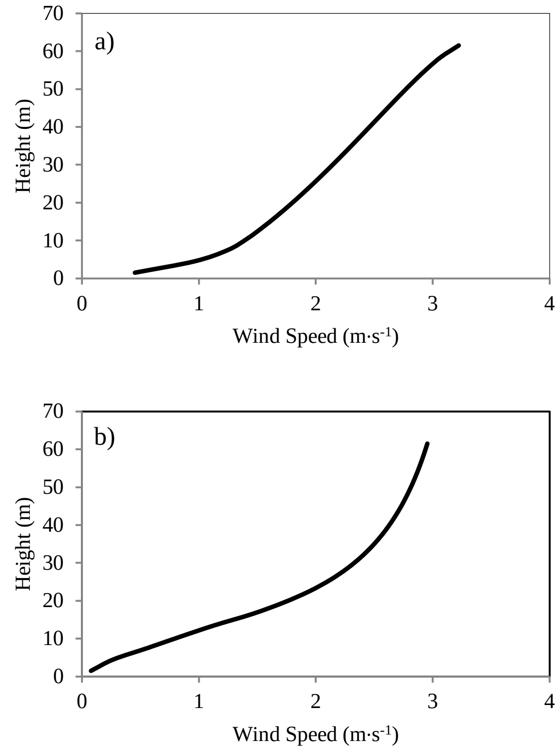

Figure 11: Vertical profile of the wind speed for two different atmospheric stability (a) unstable (b) stable

During the summer, as expected in highly dense areas, the sun rays do not reach the surface close to the ground. This phenomenon is often called the cool island effect and is created by the built environment, and it explains why the cooling demand of the site can be reduced by 75% with the CIM model.

By analysing the results obtained by the simulations, for the old city centre of Nablus an average decrease of the air temperature by 2.1°C induces a decrease in the cooling demand by 75%. This analysis shows that the wind speed has a low impact in the energy demand of buildings, which are importantly influenced by the air temperature.

CONCLUSION

The weather data provided by CIM model has in important impact in the heating and cooling demand of buildings in the old city of Nablus. Indeed, it was shown that the wind speed and the air temperature in an urban canopy can be significantly influenced by the presence of buildings. The high density of buildings in an old district as the one considered in this paper also impact the solar radiation reaching the ground surface.

Based on the modification of the local meteorological variables, it was found that the average annual heating demand of the district increases by 9% and the cooling demand of buildings reduces by 75%.

Future steps of this work will be the analysis of the outdoor human comfort in the old city of Nablus, quantifying the impact of the CIM model in the thermal sensation of pedestrians.

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REFERENCES

ADEME, 2012. Energie et Climat - Edition 2012. Agence de l'Environnement et de la Maîtrise de l'Energie, Angers.

Al-Amad, E., 1998. Continuity and change in traditional domestic architecture of Palestine: transformation of traditional concepts of house design in Nablus.

Ali-Toudert, F., Mayer, H., 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. Build. Environ. 41, 94–108. doi:10.1016/j.buildenv.2005.01.013

Ashie, Y., Thanh Ca, V., Asaeda, T., 1999. Building canopy model for the analysis of urban climate. J. Wind Eng. Ind. Aerodyn. 81, 237–248. doi:10.1016/S0167-6105(99)00020-3

Crawley, D.B., Lawrie, L.K., Pedersen, C.O., Winkelmann, F.C., 2000. Energy plus: energy simulation program. ASHRAE J. 42, 49–56.

IPCC, 2013. WORKING GROUP I CONTRIBUTION TO THE IPCC FIFTH ASSESSMENT REPORT CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS. Geneva: Intergovernmental Panel on Climate Change.

Johansson, E., 2006. Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. Build. Environ. 41, 1326–1338. doi:10.1016/j.buildenv.2005.05.022

Kämpf, J.H., Robinson, D., 2007. A simplified thermal model to support analysis of urban resource flows. Energy Build. 39, 445 – 453. doi:10.1016/j.enbuild.2006.09.002

Mauree, D., 2014. Development of a multi-scale meteorological system to improve urban climate modeling. Université de Strasbourg.

Mauree, D., Kämpf, J.H., Scartezzini, J.-L., 2015a. Multi-scale modelling to improve climate data for building energy models, in: Proceedings of the 14th International Conference of the International Building Performance Simulation Association. Presented at the 14th International Conference of the International Building Performance Simulation Association, Hyderabad.

Mauree, D., Nadège, B., Clappier, A., Kämpf, J.H., Scartezzini, J.-L., 2015b. Evaluation of building energy use: from the urban to the building scale, in: Proceedings of the 9th International Conference on Urban Climate. Presented at the 9th International Conference on Urban Climate, Toulouse.

Mirsadeghi, M., Cóstola, D., Blocken, B., Hensen, J.L.M., 2013. Review of external convective heat transfer coefficient models in building energy simulation programs: Implementation and uncertainty. Appl. Therm. Eng. 56, 134–151. doi:10.1016/j.applthermaleng.2013.03.003

Robinson, D., 2012. Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications. Routledge.

Salamanca, F., Martilli, A., Tewari, M., Chen, F., 2011. A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with WRF. J. Appl. Meteorol. Climatol. 50, 1107–1128.

Salameh, A., n.d. Towards sustainable construction systems of external walls of buildings in the West Bank of Palestine.

Santiago, J.L., Martilli, A., 2010. A Dynamic Urban Canopy Parameterization for Mesoscale Models Based on Computational Fluid Dynamics Reynolds-Averaged Navier–Stokes Microscale Simulations. Bound.-Layer Meteorol. 137, 417–439. doi:10.1007/s10546-010-9538-4

Yousof, M., 1989. General guidelines for developing and preserving the historic old city of "Nablus" - West Bank.