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An idealized study of city structure, urban climate, energy consumption, and air quality

Alberto Martilli *

Atmospheric Pollution Division, Department of Environment, CIEMAT, Spain

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ABSTRACT

The interactions between the structure of a city and the atmosphere have an impact on thermal comfort, air quality and building energy consumption for space heating and cooling. A mesoscale model, with a multilayer urban canopy parameterization, coupled with a simple building energy model is used to investigate such interactions by simulating 22 idealized cities in 3D with the same total population, but different population densities and vegetation fraction in the urban areas. Simulations are performed for summer and winter periods at mid latitude and for a hot dry climate. Results indicate that compact cities, with buildings with low surface-to-volume ratios, minimize the building energy consumption for space heating/cooling, but maximize the outdoor heat stress. For air quality, the optimum is for cities with intermediate population densities. The inclusion of vegetation is most of the time positive, and never detrimental, in this climate.

1. Introduction

The temperature and composition of the air in the Urban Canopy Layer (UCL) are the results of the fluxes of mass, energy and momentum exchanged by the air itself with the urban elements (buildings, cars, urban vegetation), and with the air of the planetary boundary layer (PBL) above. The intensity and time evolution of these fluxes is strongly affected by the city structure (size and arrangement of buildings, presence of vegetation, human activities, etc.). It is this structure that determines, for

* Address: Research Centre for Energy, Environment and Technology, CIEMAT, Edificio 70, P1.11, Avenida Complutense 22, 28040 Madrid, Spain. Tel.: +34 913466299.

E-mail address: alberto.martilli@ciemat.es

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example, the radiation budget at the urban surfaces, and the complex flow patterns in the UCL that transport heat, mass and momentum.

The UCL behaviour is important for citizen's life because it impacts air quality, thermal comfort, and the part of the building energy consumption due to space heating/cooling. Since the urban structure is the result of the human activity, it can be imagined that, by carefully planning the city structure, it is possible to control the UCL to improve air quality and thermal comfort, and reduce building energy consumption.

The main scientific question that motivates this paper is then:

Is there a climatically optimal city structure?

To answer this question a methodology is designed based on three climatically relevant variables (thermal comfort, air quality and energy consumption due to space heating/cooling), and it is applied to idealised cities.

Traditionally the problem of the interactions between city structure, energy consumption and thermal comfort, has been studied by architects, urban planners and atmospheric modellers. For example Adolphe (2001, 2009) proposed a set of indicators of simplified morphological characteristics of the energy performance of buildings and urban climate (namely density, roughness, sinuosity, occlusivity, compacity, contiguity, solar admittance, and mineralisation) that were embedded in a GIS based software called *Morphologic* that can be used to compare the environmental performance of different urban fabrics. The interaction between heat released by air conditioning (AC) systems and urban climate has been studied with an urban canopy model coupled to a building energy module by Ohashi et al. (2007) over Tokyo. They found that AC can raise the street air temperature by 1–2 °C in the business district of Tokyo; this result was confirmed by the analysis of the differences between the measured temperatures during weekdays and during weekends, when the use of AC is reduced. Salamanca et al. (2011) embedded an urban canopy model, coupled with a building energy module in a mesoscale model to simulate Houston and Madrid (Salamanca et al., 2012) and found a similar effect of the AC (1–2 °C of temperature increase compared to the case without release of heat from AC) in some parts of the city during the late evening and beginning of the night. de Munck et al. (2013) applied a similar approach over Paris using actual data of AC systems in the city and found the maximum impact to be around 0.5 °C. However, if the heat released by AC is doubled and only sensible (no latent), a scenario considered realistic for 2020, the impact increases to 2 °C, in particular during the evening and night. Masson et al. (2013) using the same modelling approach, again over Paris, found that "extending the nearby forests by 30%, favoring short farm-to-consumer circuits and using lighter colored building materials will decrease the urban heat island, reducing the mortality during heat waves as well as the need for air-conditioning". This study is very relevant because it shows how the modelling approach can be used as a tool to help urban planning. Similarly, Loughner et al. (2012) used a mesoscale model with an urban canopy parameterization to examine the effect of vegetation in Washington DC and Baltimore. They found that urban vegetation can lower air temperature at street level by up to 4.1 °C.

The interactions between air quality and urban structure, on the other hand, have been studied, for example, by Martins (2009) who investigated them over idealized cities, and over the region of Porto (Portugal). Baik et al. (2012) on the other hand, used a microscale CFD (Computational Fluid Dynamics) model to simulate the impact of green roofs, and found that they increase the mixing in the canopy during night, with consequent benefit for air quality. Taha (2008) investigated, with a mesoscale model coupled with a photochemical model, how a change in the albedo of the roofs of Los Angeles can have an impact on the ozone concentration. The idea is that an increase of albedo reduces the air temperature over the city and, since reaction constants responsible of Ozone formation are temperature dependents, the Ozone is also reduced. Their model results indicate a potential reduction of 10–15% of Ozone levels due to an increase of albedo.

All the studies mentioned above focussed, in some cases with a very high level of detail, either on the links between urban structure, urban climate and energy consumption, or between urban structure and air quality, but never on the interactions between all the aspects. The work with the motivations more similar to those of the present paper is probably the one of Oke (1988) where he tried to define the best street geometry to optimize thermal comfort and air quality. However, the differences are in the fact that he used urban canyon field studies and scale models for his research, while here a mesoscale model is used, and the aim is to consider not only the microscale, but also the interactions

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