Exploring scale-adaptive representations and distinctive signatures of cities using the Multi-Resolution Analysis

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1. INTRODUCTION

The need of atmospheric and pollution dispersion modeling at various scales urges that urban morphology data can be appropriately represented at the different scales in atmospheric modeling (Britter and Hanna 2003). In doing so, the spatial complexity of the underlying surfaces must be carefully addressed, and the model grid resolution must be commensurate with the desired outcome; as a result, for any model grid resolution, the unresolved sub-grid information content can be quite large (Ching, 2012). Mesoscale meteorological models have used a range of methods to account for the effects of sub-grid scale buildings and urban surface cover in order to better predict the wind, turbulence, and concentration fields. A set of UCPs describes the surface cover properties (e.g. aerodynamic roughness length, albedo), building height characteristics (e.g. mean building height $\bar{H}$, standard deviation), building volume and inter-building spacing characteristics (e.g. building plan λ_p and frontal area densities λ_f , sky view factor), surface material properties (e.g. emissivity, density). The inclusion of these UCPs into the model depends on the processes that are simulated and the spatial and temporal scales of interest. Although these urban morphological measures are useful in certain type of problems, they are unable to describe uniquely or provide a distinctive signature of the urban area or the city in atmospheric modeling; two cities or urban areas could yield the same or very similar UCPs, while being quite different in morphology and thereby in aerodynamic behavior. In addition these values for example $\bar{H}$, λ_p , depend on the size of the domain (neighbourhood) and may not necessarily be representative/appropriate of the scale/grid of the model.

Consequently, there is a need for finding a method which can take into consideration the inherent information of urban morphology, and convey this information to multi-scale modeling studies - without discarding redundant details - in some manageable way (Ching, 2012; Mouzourides et al., 2013).

In this paper we consider the urban areas of four North-American cities, New York City, Oklahoma, Phoenix and Seattle, as a 2D signal that varies in space, and Multi-Resolution Analysis (MRA) is applied, in order to reveal their multiscale nature.

2. THEORY AND METHODOLOGY

In this paper, the selection of MRA as a tool to analyze the urban domain was motivated by its capacity for multi-scale sampling without discarding redundant details of smaller scales when used to sample signals over larger scales (Mouzourides et al., 2014). To achieve a MRA, the existence of finite-energy function $\varphi(t)$ (called as scaling function) of the function space $L^2(R)$, is

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necessary in order to generate a nested subspaces $\ldots V_j \subset V_{j+1} \subset V_{j+2} \ldots$, where j are integer indices, (Mallat, 2009). A discrete signal, f_s, of either time or space to be analyzed by MRA is assumed to belong in V_0. This space is assumed to contain information down to a scale equivalent to the sampling period, the time between different values of f_s. The translates φ(t-nτ) of scaling function $\varphi(t)$, generate an orthogonal basis of V_0. Multi-scale analysis for a given signal $f \in L^2(R)$ is implemented by projecting f on an f_j in V_j subspace by, $f_j = \sum_n \langle f, \varphi_{j,n} \rangle \varphi_{j,n}(t)$ where f_j is interpreted as the *approximation* of f at scale 2^jτ. In order to obtain an *approximation* f_{j+1} at the next higher scale, given by 2^{j+1}τ, the details at scale 2^jτ should be removed from f_j. In MRA these details are assumed to be held in the orthogonal complement, denoted by W_j, of V_{j+1} in V_j. It can be proved that W_0 can be generated by a wavelet function $\psi(t)$, which can be derived from the scaling function $\varphi(t)$. The projection of an $f \in L^2(R)$ in W_j is given by $d_j = \sum_n \langle f, \psi_{j,n} \rangle \psi_{j,n}(t)$, where d_j is the detail removed from fj in order to obtain f_{j+1}.

Therefore $f_j \in V_j$ can be expressed as:

$$f_j = f_k + \sum_{l=j+1}^{k} d_l \qquad (1)$$

Similar to a one-dimensional discrete signal, a two-dimensional discrete signal is assumed to belong to V_0^2 and to contain information down to scale (δx x δy), where δx and δy are the sampling rates across the dimensions x and y respectively. The corresponding to Eq. 1 for $f_j(x,y)$ is given by:

$$f_j(x,y) = f_k(x,y) + \sum_{l=j+1}^{k} d_l^H(x,y) + d_l^V(x,y) + d_l^D(x,y) \qquad (2)$$

where H,V,D stand for horizontal, vertical and diagonal *details* respectively.

The 2-D data information-signal that was used in this paper is simply a pixilated image of the urban area, where the value of each pixel refers to the height of the roughness element above the ground. Therefore, it gives a full, three-dimensional description of the urban building morphology of the area. In the representation of the λ_p as a pixilated image, each pixel of the image with the original (highest) resolution, a pixel that represents part of a built area or a building gets a value of one (1) while open, unbuilt pixel areas get a value of zero (0). The MRA was applied to all urban datasets of four North-American cities (New York City, Phoenix, Seattle as well as Oklahoma) and was implemented using the wavelet toolbox of Matlab. Haar scaling and wavelet functions are recommended for MRA analysis of urban building datasets because their functional form is a sequence of rescaled "square-shaped" functions.

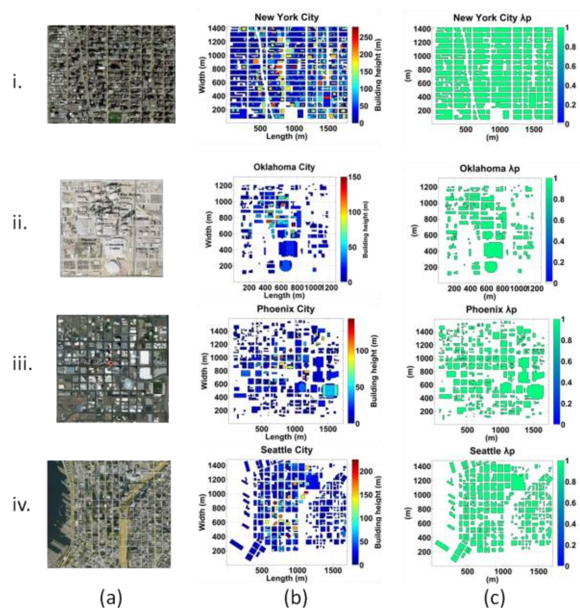

Figure 1: Building elevation datasets of (i) New York (1420m x 1780m), (ii) Oklahoma (1310m x 1280m), (iii) Phoenix (1590m x 1730m) and (iv) Seattle (1480m x 1700m). (a) Left side images depict the Google image of study area. (b) Right side images depict the digitized building elevation datasets. In all cases, each pixel corresponds to 1m x 1m.

3. RESULTS AND DISCUSSION

In this section the results obtained from the MRA of the different urban building datasets are presented and discussed. Before proceeding, however, we demonstrate briey how some of the theory and the methodology ideas can be interpreted through the output results Figure 2 depicts the last three out of the ten levels of approximations that the MRA yielded for each urban domain: approximations 8, 9, 10. Approximation 8 corresponds to a 256x256 pixels resolution, and for Approximation 9 and 10 to 512x512 and 1024x1024 pixels respectively. The colour of each sub-image domain corresponds to the characteristic/dominant building height of that sub-image/subdomain.

Starting from the original digitized image of built height of the area, the edges and corners of the buildings in the image obtained from Approximation A1, are smoothed, simply because they are adjacent to non-built, empty space. The removed details that cause the edges and corners to smooth out during the approximation process are reconstructed in the detail part as Total Detail.

Moreover, for every level of analysis, the component of approximation is associated with its corresponding component of total details which is the summation of horizontal details (W-E or x-direction), vertical details (N-S or y-direction) and diagonal details.

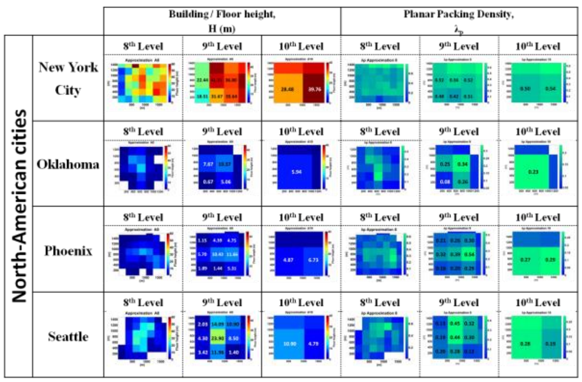

Figure 2: MRA deduced results (three last levels) of $\bar{\bar{H}}$ and λ_p parameter for four North-American cities (i) New York, (ii) Oklahoma, (iii) Phoenix and (iv) Seattle.

Some key elements for the interpretation of the MRA results are that in the approximation components, the colourbar depicts the average built floor height of the dataset for the corresponding scale of level of analysis; respectively, for the cases of the details components, the colourbar depicts the difference of the built or height of neighbouring cells and the label refers to the cell size of the corresponding approximation component. For more details in how the theoretical ideas are envisaged and manifested through the MRA output results can be found in Mouzourides et al. (2013).

The above MRA-deduced results for the $\bar{H}$ and λ_p, were used together with the morphometric model by Kastner-Klein and Rotach (2004) in order to derive spatially-varying scale-adaptive descriptions of z_0 and d. Figure 4 depicts the calculated results of the urban morphological parameters of z_0 and d, for North-American cities. Therefore, the results show that Phoenix, Oklahoma have similar values of z_0 and New York the highest (z_0 = 2.07m, the main value of the central cell). In addition, Figure 3 shows that New York has the highest d=25.59m, while Oklahoma, Phoenix and Seattle have smaller zero-plane displacement values (3.84m, 3.39m and 7.74 respectively)

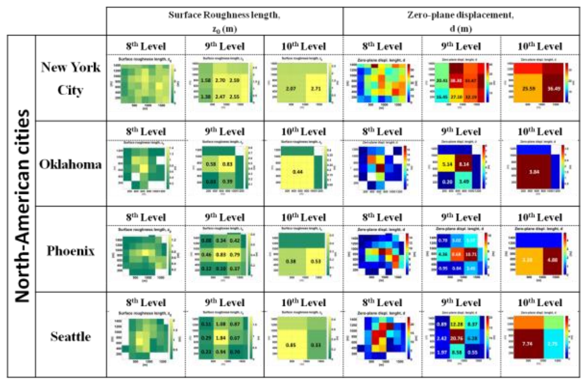

Figure 3: Calculated parameter (three last levels) of z_0 and d for four North-American cities (i) New York, (ii) Oklahoma, (iii) Phoenix and (iv) Seattle.

Moreover, we present an example which highlights the potential of methodology to distinguish between ostensibly similar datasets of urban morphology. Phoenix and Seattle have the same value of λ_p at Level 10, which corresponds to a cell size of 1024m x 1024m. However, at Level 9, the results are entirely different. Respectively, for the case of the city of Seattle, the removal of information, in going from the approximation at Level 9 to Level 10, is its corresponding result of total details at Level 10. Therefore, what becomes obvious is that although both cities have the same value of λ_p for the cell size of 1024m x 1024m, at level 9 of the analysis entirely different results are obtained for each city. On the other hand, the third column of Fig. 4, depicts the total details across all the levels of analysis, according to summation $\sum_{l=j+1}^{k} d_l^H(x,y) + d_l^V(x,y) + d_l^D(x,y)$ that were removed from the original urban building signal, in order to obtain the λ_p at approximation at Level 10. Therefore by having the approximation of the last level of analysis and the total details of all

MRA levels, we can recover the original urban building"signal".

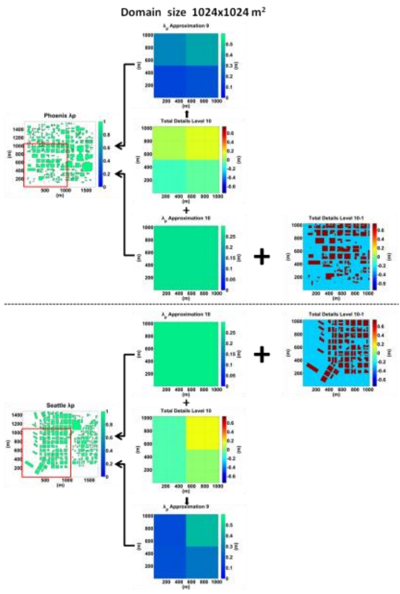

Figure 4: Example of MRA approximations and total details of analysis of λ_p 's 2-D urban building database of Phoenix and Seattle.

Due to this capability of retaining the details removed at each level the MRA can encode the unique information that an urban building database contains.

4. CONCLUDING REMARKS:

In this paper we illustrate how the MRA can be applied on a number urban building databases, in order to provide scale-adaptive, spatially-varying representations of the urban building databases. Specifically, by analyzing the urban signal into an approximation and a detail, different representations of the urban building database can be obtained with respect to different scales or resolutions, namely levels of analysis. This provides a sound basis for rigorous inter-comparisons between different urban datasets as well as for appropriate representations - suitably adapted to the referenced resolution for mesoscale models The spatial or structured representation of the MRA results envisions homogeneity and heterogeneity and enables its quantification. Furthermore, it was shown that MRA enables useful methods of determining scale-adaptive and spatially-varying descriptions of aerodynamic urban canopy parameters as a given example of determination of z0 and d.
Finally, through a discussion of examples it was shown that MRA can provide an innovative means to distinguish between urban databases and cities,and in the light of the presented results it can be said that MRA encodes the unique information of an urban morphology database the same way as the DNA encodes the genetic information of all living organisms of the same species - in essence providing a DNA-like description of a city. For models, the MRA provides gridded and scaled attributes as well as sub-grid information for a hierarchy of grid sizes

5. REFERENCES:

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