# EVALUATION OF A HIGH RESOLUTION ATMOSPHERIC URBAN-SCALE (CANOPY) MODEL FOR ENERGY APPLICATIONS IN STRUCTURED AREAS

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## ABSTRACT

A reliable estimation of the energy consumption of buildings including the short term prediction (1-4 days) of air conditioning loads, requires the use of trustworthy predictions of meteorological parameters such as temperature, solar radiation and vector rate at a very high spatial resolution i.e. hundreds of meters over the built-up areas. The use of atmospheric mesoscale models (computational cells in the order of kilometres) provides very sparse information since the extent of urban areas is practically covered by less than ten computational cells in most applications. On the other hand, the implementation of these standards in high resolution requires an understanding of the physical configurations of the pattern when the distance between the computing nodes approaches the main scale of the phenomena one wishes to forecast.

The current work is part of a project the aim of which is the development and evaluation of a high resolution atmospheric urban-scale model to simulate the aerodynamic and thermal effects of urban surface characteristics on the atmosphere and provide detailed meteorological parameters required for energy studies in structured areas. The model is based on a microscale Computational Fluid Dynamics (CFD) type numerical model. It will be applied to a large area of Kozani city instead of the typical application in isolated streets or buildings, which is frequently met in the literature. This model will be coupled with a mesoscale atmospheric model which will provide the boundary conditions to the CFD model. For this purpose the Atmospheric Pollution Model (TAPM) will be used within the research effort. In the present paper, the evaluation of TAPM at very high spatial resolution is presented. Control runs of the model developed were carried out over the wider area of Kozani, and the results were evaluated according to observed measurements of surface meteorological parameters.

**Keywords:** TAPM, CFD, model evaluation, energy applications, urban canopy

## 1. Introduction

Energy studies in buildings and especially reliable calculation of their energy consumption including short-term forecast of air-conditioning loads requires the use of a reliable forecast of various meteorological parameters at a very high resolution (hundreds of meters) over an urban area. Mesoscale models at a resolution of a few kilometers provide very coarse information since an urban area is merely covered by single digit number of computational cells in most of the applications. On the other hand, application of mesoscale models at the micro-scale requires a thorough understanding of the physical mechanisms and parameterizations of the model when the size of the computational cell is comparable to the main scale of the phenomena one wishes to forecast. The parameterization problem is also directly associated with the selection of the important parameters such as the roughness length. Moreover, heterogeneities in land-surface characteristics that occur in transitions from a city to the rural countryside can significantly alter the lower part of the atmospheric boundary layer through mechanic and thermodynamic interactions.

The current work is part of a project aiming to address both numerically and experimentally the above issues. A Computational Fluid Dynamics (CFD) type numerical model will be the basis for a high resolution atmospheric urban- scale model to be developed and applied in a large area of the city of Kozani instead of the typical application in isolated streets or buildings which is frequently met in the literature (Richards *et al*. 2002, Mochida and Lun 2008). This model will be further coupled with TAPM, a mesoscale atmospheric model which will provide the boundary conditions to the CFD model. Measurements of surface meteorological paramenters as well sodar wind and radiometer temperature profiler measurements over an urban area will be conducted to evaluate the performance of the models. In the present paper, the evaluation of TAPM at very high spatial resolution is presented. Control runs of the model were carried out over the wider area of Kozani, and the results were evaluated according to measurements of surface meteorological parameters.

## 2. Model's configuration and performance indices

TAPM was configured with five (nested) grids of 21x21 horizontal points with 30km, 10km, 3km, 1km and 300m grid spacing, and 45 vertical levels ranged from 10m up to , 8000 m. The TAPM was used to model the meteorology of July 2013 and January 2014 in the Kozani region. Once the aforementioned parameters were defined, the topography of the area in high resolution (90m, STRM3) was imported. TAPM evaluation was performed by producing meteorological forecasts in four selected sites located in Xaravgi, Kato Komi, Petrana and TEI.

For each monitoring station two performance indices were calculated using hourly data for each simulation day: the Index of Agreement (IOA) and the Root-Mean-Square-Error (RMSE). The IOA (Triantafyllou *et al*, 2011) is a measure of how well predicted variations around the observed mean are represented and ranges from 0 to 1, with a larger number indicating a more accurate forecast. This index was proposed by Willmott (1981) as an alternative for r (correlation coefficient) and $r^2$ (coefficient of determination), since the latter are not consistently related to the accuracy of prediction. An IOA greater than 0,5 is generally considered as a good meteorological prediction, based on other models reported in the literature (Hurley *et al*., 2001; P.Zawar-Reza *et al*, 2005). Statistics also include a breakdown of root mean square errors (RMSE) into systematic (RMSE_S) and unsystematic (RMSE_U) components. Low RMSE values in a model indicate that the model explains most of the variation in the observations, while in a model lacking bias, RMSE_S should approach zero, and consequently RMSE_U should be close to RMSE. According to Pielke (1984), a model predicts with skill if two conditions are satisfied: (a) the standard deviations of the predictions and observations are approximately the same; and (b) RMSE is less than the standard deviation of the observations.

## 3. Results and discussion

System predictions of meteorology were extracted at the nearest grid point to each of the four meteorological stations. Specifically for monitoring sites TEI and Xaravgi on the inner grid (300m spacing) and for monitoring sites Petrana and Kato Komi on the fourth grid (1km spacing) at 10m above the ground for winds and at screen level for temperature. January and July were selected for the current work, since they are the coldest and the hottest months of the year, respectively. Actually, the lowest mean monthly temperature in Kozani (5,1°C) was recorded in January while the highest mean monthly temperature in the same area (22°C) was observed in July (see Tables 1 and 2).

### 3.1. Results for January 2014

Table 1(a) shows statistics for predicted versus observed near-surface temperature (T) for each of the monitoring sites and for an average (AVG) over all of the sites for January 2014. According to the correlation coefficient (CORR), results seem to have a strong linear correlation since the coefficient values range from 0.79-0.84. The values of IOA were much higher than 0.5, approaching 1 (full agreement). The highest IOA was estimated at 0.95 for Xaravgi, while the lowest value occurred in Kato Komi (0.82). The IOA value for temperature was greater than 0.8, a typical result for the TAPM (Thatcher *et al*., 2010, P. Zawar-Reza *et al*., 2005). The RMSE indicator for temperature was low throughout the studied period ranging from 1.7°C to 4.5°C. The SKILL_V indicator shows that the results presented credibility since values are close to 1, ranging from 0.67 to 0.75. The indexes SKILL_R for the average of all stations and SKILL_E for temperature were less than 1. In general, it was found that during January 2014 the model results concerning temperature were well correlated with the observed measurements. However, on days with temperatures lower than 0°C, the model predicted values that were somewhat higher than 0°C, which should be further examined.

Tables 1(b) and 1(c) show statistics for near-surface horizontal wind components (u, v). The average of IOA for “u” is 0.36, with a higher value in Kato Komi (0.53) indicating that the predicted values of the model for this station are good. The lowest value was found in Petrana (0.12). The highest value of component wind “v” was observed in Kato Komi (0.63) and the lowest in Petrana (0.11). The mean IOA for the “v” wind component was equal to 0,41, indicating a better agreement between observed and calculated values for the “v” component related to the “u” one. The RMSE values were relatively low for all stations for both components “u” and “v”, with Petrana exhibiting the highest values (5.42 and 9.59 respectively). The measures of skill show that, on average, the standard deviations of winds were predicted well with their ratio (SKILL_V) being 0.62 to 1.11 for “u”, “v”, compared to the ideal value of 1.0, with the exception of Petrana (0.24 and 0.13). For both wind components (u, v) the SKILL_E is less than 1.0 (0.13-0.98), which indicate skill, with the exception of TEI (1.11) and Xaravgi (1.42). The results show that the temperature for January 2014 was predicted well.

### 3.2. Results for July 2013

Table 2(a) shows statistics for predicted versus observed near-surface temperature (T) for each of the monitoring sites and for an average (AVG) over all of the sites for July 2013. The results according to the correlation coefficient (CORR) seem to have a strong linear correlation since the coefficient values were equal to 0.93. The values of IOA ranged between 0,73 and 0,95, indicating full agreement. The RMSE indicator for temperature was low throughout the period ranging from 0.88°C to 3.61°C. The reliability of the model is concluded and the values of RMSE_S are close to 0 on all stations. The SKILL_V indicator shows that the results showed credibility as values were close to 1 (0.91 to 1.04). The index SKILL_R for the average of all stations was less than 1 (0.56), as well as and the index SKILL_E (0.24).

The results for the components of the wind (u, v) are presented in Table 2 (b) and 2 (c) respectively. The values of IOA for the components of the wind (u, v) did not exceed the value of 0.47 for all stations. The lowest price was calculated for component “v” in Petrana (0.29). The average of IOA for (u, v) was 0.39, which means that there is a good agreement between observed and predicted values. The average RMSE for (u, v) was quite low for all stations for both components (1,27 m/s-2,03 m/s).

The measures of skill show that on average the standard deviations of winds were predicted well with their ratio (SKILL_V) ranging from 0.87 to 1.62, compared to the ideal value of 1.0. Values of SKILL_E were satisfactory calculated under unity with the exception of TEI (1.21) and Xaravgi (1.02). The results show that the temperatures for July 2013 were predicted very well.

## 4. Conclusions

The Air Pollution Model (TAPM) was used to model the meteorology of January 2014 and July 2013 in the Kozani region. The model predictions were compared with data from four surface meteorological stations in the region.

Generally, the results showed that TAPM has demonstrated good performance in predicting the near-surface meteorology in the Kozani region for both a winter (January) and a summer (July) month. The model predicted well, although the predictions of temperature for July were better than for days with temperatures lower than 0°C in January. The IOA ratio ranged from 0.73

(Xaravgi, July 2013) to 0.95 (Xaravgi, January 2014). The average IOA of the wind speed was close to 0.4, showing a relatively good agreement between predicted and measured values.

## ACKNOWLEDGMENTS

The work was carried out under the program “Archimedes III”, Subproject 10 "Development and evaluation of a high resolution atmospheric urban canopy model for energy applications in structured areas" funded by the Greek Ministry of Education and Religious Affairs.

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**Table 1 (a):** Temperature (°C) **(b)** West-east (u) and **(c)** south – north (v) component of the wind (m s$^{-1}$) statistics for TAPM simulation of January 2014 at meteorological monitoring sites.

| SITE NAME | MEAN_OBS | MEAN_PRED | STD_OBS | STD_PRED | CORR | IOA | RMSE | RMSE_U | RMSE_S | SKILL_V | SKILL_R | SKILL_E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Temperature ($^{o}$C) | | | | | | | | | | | | |
| **TEI** | 5,10 | 6,05 | 4,08 | 2,74 | 0,79 | 0,84 | 2,67 | 3,02 | 1,95 | 0,67 | 0,65 | 0,74 |
| **XARAVGI** | 5,30 | 6,08 | 3,96 | 2,74 | 0,81 | 0,95 | 1,69 | 1,49 | 0,79 | 0,69 | 0,43 | 0,38 |
| **PETRANA** | 5,20 | 7,03 | 4,23 | 2,77 | 0,84 | 0,92 | 3,05 | 3,20 | 2,24 | 0,65 | 0,72 | 0,76 |
| **K.KOMI** | 5,10 | 8,85 | 3,68 | 2,76 | 0,72 | 0,82 | 4,55 | 2,16 | 0,29 | 0,75 | 1,24 | 0,59 |
| **AVG** | 5,18 | 7,00 | 3,99 | 2,75 | 0,79 | 0,88 | 2,99 | 2,47 | 1,32 | 0,69 | 0,76 | 0,62 |
| b) West-east (u) component of the wind (m s$^{-1}$) | | | | | | | | | | | | |
| **TEI** | 0,15 | -0,11 | 1,35 | 1,50 | -0,01 | 0,38 | 2,04 | 1,50 | 1,38 | 1,11 | 1,51 | 1,11 |
| **XARAVGI** | -0,62 | 0,05 | 1,13 | 1,83 | -0,06 | 0,42 | 1,52 | 1,60 | 1,33 | 1,62 | 1,35 | 1,42 |
| **PETRANA** | 0,35 | -0,04 | 5,22 | 1,23 | -0,03 | 0,12 | 5,42 | 0,78 | 0,47 | 0,24 | 1,04 | 0,15 |
| **K.KOMI** | -1,21 | 0,03 | 1,45 | 1,26 | -0,18 | 0,53 | 2,17 | 0,85 | 1,71 | 0,87 | 1,50 | 0,59 |
| **AVG** | -0,33 | -0,02 | 2,29 | 1,46 | -0,07 | 0,36 | 2,79 | 1,18 | 1,22 | 0,96 | 1,35 | 0,52 |
| c) South-north (v) component of the wind (m s$^{-1}$) | | | | | | | | | | | | |
| **TEI** | -0,20 | 0,00 | 1,72 | 1,64 | 0,00 | 0,42 | 2,38 | 1,68 | 2,08 | 0,95 | 1,38 | 0,98 |
| **XARAVGI** | 0,30 | 0,10 | 1,72 | 1,83 | -0,04 | 0,49 | 1,61 | 1,52 | 0,12 | 1,06 | 0,94 | 0,88 |
| **PETRANA** | -1,10 | 0,10 | 9,45 | 1,26 | 0,00 | 0,11 | 9,59 | 1,21 | 0,36 | 0,13 | 1,01 | 0,13 |
| **K.KOMI** | 0,20 | 0,00 | 1,82 | 1,22 | 0,09 | 0,63 | 2,11 | 0,93 | 0,96 | 0,67 | 1,16 | 0,51 |
| **AVG** | -0,20 | 0,05 | 3,68 | 1,49 | 0,01 | 0,41 | 3,92 | 1,34 | 0,88 | 0,71 | 1,12 | 0,36 |

**Table 2 (a):** Temperature (°C) **(b)** West-east (u) and **(c)** south-north (v) component of the wind (m $s^{-1}$) statistics for TAPM simulation of July 2013 at meteorological monitoring sites.

| **SITE NAME** | **MEAN_OBS** | **MEAN_PRED** | **STD_OBS** | **STD_PRED** | **CORR** | **IOA** | **RMSE** | **RMSE_U** | **RMSE_S** | **SKILL_V** | **SKILL_R** | **SKILL_E** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Temperature (ºC) | | | | | | | | | | | | |
| **TEI** | 22,00 | 23,00 | 4,29 | 4,48 | 0,93 | 0,95 | 1,95 | 1,78 | 0,41 | 1,04 | 0,45 | 0,41 |
| **XARAVGI** | 22,00 | 23,00 | 4,35 | 4,49 | 0,92 | 0,73 | 0,88 | 0,79 | 0,49 | 1,03 | 0,20 | 0,18 |
| **PETRANA** | 24,00 | 24,00 | 4,23 | 4,42 | 0,93 | 0,90 | 3,61 | 0,81 | 0,38 | 1,04 | 0,85 | 0,19 |
| **K.KOMI** | 25,00 | 26,00 | 5,03 | 4,57 | 0,93 | 0,90 | 3,57 | 0,90 | 0,93 | 0,91 | 0,71 | 0,18 |
| **AVG** | 23,25 | 24,00 | 4,48 | 4,49 | 0,93 | 0,87 | 2,50 | 1,07 | 0,55 | 1,01 | 0,56 | 0,24 |
| b) West-east (u) component of the wind (m $s^{-1}$) | | | | | | | | | | | | |
| **TEI** | 1,10 | 0,00 | 1,35 | 1,50 | -0,01 | 0,40 | 2,45 | 1,64 | 1,86 | 1,11 | 1,81 | 1,21 |
| **XARAVGI** | -0,80 | -0,20 | 1,13 | 1,83 | 0,08 | 0,41 | 1,27 | 1,15 | 0,92 | 1,62 | 1,12 | 1,02 |
| **PETRANA** | -0,20 | 0,00 | 5,22 | 1,23 | 0,05 | 0,33 | 2,29 | 1,14 | 0,33 | 0,24 | 0,44 | 0,22 |
| **K.KOMI** | 0,10 | 0,00 | 1,45 | 1,26 | 0,01 | 0,41 | 2,35 | 0,86 | 1,04 | 0,87 | 1,62 | 0,59 |
| **AVG** | 0,05 | -0,05 | 2,29 | 1,46 | 0,03 | 0,39 | 2,09 | 1,20 | 1,04 | 0,96 | 1,25 | 0,52 |
| c) South-north (v) component of the wind (m $s^{-1}$) | | | | | | | | | | | | |
| **TEI** | 0,30 | 0,10 | 1,78 | 1,70 | 0,09 | 0,47 | 2,36 | 1,76 | 2,16 | 0,96 | 1,33 | 0,99 |
| **XARAVGI** | 1,20 | 0,10 | 1,77 | 2,03 | 0,00 | 0,41 | 1,55 | 1,47 | 0,11 | 1,15 | 0,88 | 0,83 |
| **PETRANA** | 0,60 | -0,20 | 0,91 | 2,21 | -0,04 | 0,29 | 2,53 | 1,27 | 0,18 | 2,43 | 2,78 | 1,40 |
| **K.KOMI** | 0,90 | 0,00 | 1,66 | 1,66 | 0,00 | 0,39 | 2,48 | 0,89 | 0,66 | 1,00 | 1,49 | 0,54 |
| **AVG** | 0,75 | 0,00 | 1,53 | 1,90 | 0,01 | 0,39 | 2,23 | 1,35 | 0,78 | 1,38 | 1,62 | 0,88 |