18th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 October 2017, Bologna, Italy

THE IMPACT OF TOPOGRAPHY AND SEA SURFACE TEMPERATURE ON THE EVOLUTION OF THE URBAN BOUNDARY LAYER

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Abstract: In applications of atmospheric dispersion modelling, the boundary layer height (BLH) determines to a large extent the spatial structure of the horizontal and vertical mixing of pollutants at time scales of a few hours. The estimation of BLH with the use of numerical models is influenced by various model parameters, such as the grid resolution and land use data, as well as by the surface parameters in the study area. In this study, the non-hydrostatic mesoscale meteorological model MEMO is used to simulate the development of the urban boundary layer (UBL) in Athens, Greece with emphasis on the diurnal BL patterns, their spatial variability and their dependence on local topographical features. A comparison between the model's existing land-surface scheme and a newly-introduced scheme is carried out in the first part of the paper. In the second part of the work, the effects on the BLH caused by the complex topography of the Attica peninsula are studied by introducing an artificial topography where prominent features around the city of Athens are removed. The results indicated that both the surface parameterisation and the topography of the study area have an important and complex impact on the evolution of the BLH.

Key words: *Dispersion modelling, Atmospheric boundary layer, Anthropogenic heat flux, Sea surface temperature*

INTRODUCTION

The simulation of the urban boundary layer's (UBL) temporal development is an integral component of dynamical modelling of the lower troposphere, as well as an important factor in the application of atmospheric pollutant dispersion models. In a typical application of dispersion modelling, the boundary layer height (BLH) determines the spatial extent of the horizontal and vertical mixing of pollutants at time scales of a few hours. The direct estimation of the evolution of UBL from standard meteorological measurements involves uncertainties related to the parameter definition and the interpretation of vertical profile data, particularly under stable conditions. Furthermore, the required high frequency (2 hours or less) and spatial accuracy of profile information relevant to pollutant dispersion effects is impossible to be achieved by experimental setups, especially over complex topographies. The performance of several proposed schemes for the estimation of the BLH, either from measured or calculated meteorological profiles, is reviewed in Seibert et al. (2000). When the BLH is estimated with the use of numerical models, it is expected that various model parameters, such as the grid resolution and land use data, as well as surface thermophysical parameters will influence the obtained results. On the other hand, such calculations provide the only means of studying the effects of local topography and land use on the UBL structure throughout relatively extended areas and especially in cases of complex topography. In this study, the non-hydrostatic mesoscale meteorological model MEMO (Moussiopoulos et al., 2012) is used to simulate the development of the UBL in Athens, Greece with emphasis on the BLH patterns, their spatial variability and their dependence on local topographical features. A comparison between the model's existing land-surface scheme and a newly-introduced surface scheme based on a more refined surface classification is presented, where the sea- and land-surface temperature and albedo input fields were derived from satellite data. In the second part of the work, the aim is to provide an insight on the effects on the BLH attributed to the complex topography of the Attica peninsula. To this end, a model run using completely flat topography over the land areas is studied.

METHODOLOGY AND CASE STUDY DESCRIPTION

The Greater Athens Areas (GAA) was selected as case study (Figure 1) for validating the system, as it represents a prototypical example of a complex topographical configuration. The computational grid has 100×100 cells in the two horizontal directions with a constant resolution of 1 km, while a coarse 300×300 km^2 mesoscale grid with a 3 km resolution is used in a one-way coupled configuration to provide the fine grid with appropriate lateral conditions. For the determination of initial and boundary conditions of the coarse grid, radiosondes data from two airport stations were used. A 48-hour meteorological period during September the 19th and 20th, 2002 was studied. A set of four model configurations were used, corresponding to different combinations of surface property parameterisations and physics schemes (Table 1).

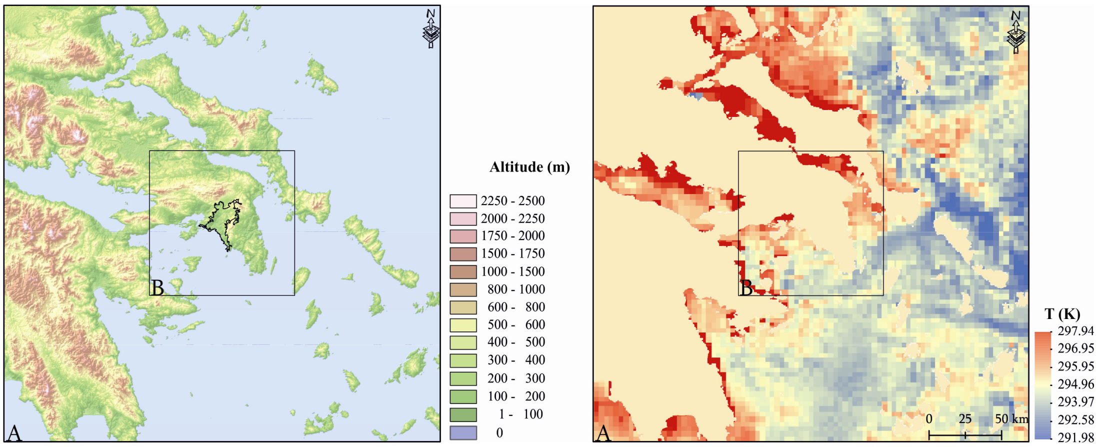

Figure 1. Configuration of nested MEMO grids (left) and Sea Surface Temperature map (right) used as input for the Greater Athens Area study

For the Athens area study, a comprehensive input database was developed by remote sensing image processing (Nitis, 2016). A detailed orography dataset was derived from the Shuttle Radar Topography Mission - SRTM/90 m database. The land use dataset originated from the Corine Land Cover 2000 (CLC 2000) database, which includes 44 land use (LU) types and were reclassified to seven LU types (A1 configuration) or eleven LU types for a more accurate representation of the urban environment (configurations B1, B4 and B4f). For the latter configuration, initial Land and Sea Surface Temperature maps were derived from the Moderate-resolution Imaging Spectro-radiometer (MODIS) instruments while the spatial distribution of roughness length was calculated using simple empirical relationships between satellite-based radiometry and vegetation physiology. Anthropogenic heat release is one of the most important causes of the urban heat island and it impacts the UBL (Falasca *et al.*, 2016). In this study, the anthropogenic heat discharge (Q_f) was estimated based on the urban canopy energy balance equation on the basis of data from a spaceborne thermal emission and reflection radiometer in combination with ground meteorological data (Nitis, 2016).

For obtaining horizontal maps of the BLH over the study area on a hourly basis, the methodology of Deardorff (1974) was applied on the basis of the hourly three-dimensional prognostic fields calculated by MEMO.

Table 1. Case and MEMO model setups used in the Athens area study

<table>
<tr><th>Model setup</th><th>LU classification</th><th>Surface parameters</th><th>Sea surface temperature</th><th>Anthropogenic heat flux</th><th>Topography</th></tr>
<tr><td>A1</td><td>7 classes</td><td>Literature</td><td rowspan="2">Constant</td><td rowspan="2">No</td><td rowspan="3">Real</td></tr>
<tr><td>B1</td><td rowspan="3">11 classes</td><td rowspan="3">Remote-sensing products</td></tr>
<tr><td>B4</td><td rowspan="2">Varying (from satellite data)</td><td rowspan="2">Derived from satellite products</td></tr>
<tr><td>B4f</td><td>Flat</td></tr>
</table>

RESULTS AND DISCUSSION

In order to observe the development of the UBL, vertical sections of the wind, temperature and TKE hourly fields were studied. The sections were taken along the NNE-SSW direction, which is the direction of the prevailing winds in the Attica area. Although the introduction of different parameterisations is causing differentiations in the corresponding predicted wind fields, in the following discussion it is assumed that the weak wind field effects do not significantly alter the BLH structure to the point of rendering any comparison inconclusive. The vertical sections for September 20th, 2002 12:00 LST, shown in Figure 2, indicate typical summertime weak synoptic conditions which favour the development of a distinct thermal plume over the urban area. Following the weak surface flow, the plume is transported downwind towards the northern suburban areas and through the opening between the Penteli and Parnitha mountain ridges. This characteristic structure confirms the role of those topographic features in influencing the development of the UBL, at least under weak anticyclonic conditions. Similar features can be observed in the TKE vertical sections, where significant production can be observed at least over the lower 1 km over the urban area, attributed to the presence of increased surface roughness, enhanced heat fluxes and multiscale surface in-homogeneities in these areas. Both in the TKE and temperature fields, the B1 model setup predicts a more pronounced urban plume structure compared to the simpler A1 setup, with strongly defined boundaries between the observed internal BLs near the shorelines and two distinct temperature maxima on the southern part of the urban area. These features were found to represent a clear improvement in regard to the agreement with measurements, compared to the A1 setup (Nitis, 2016).

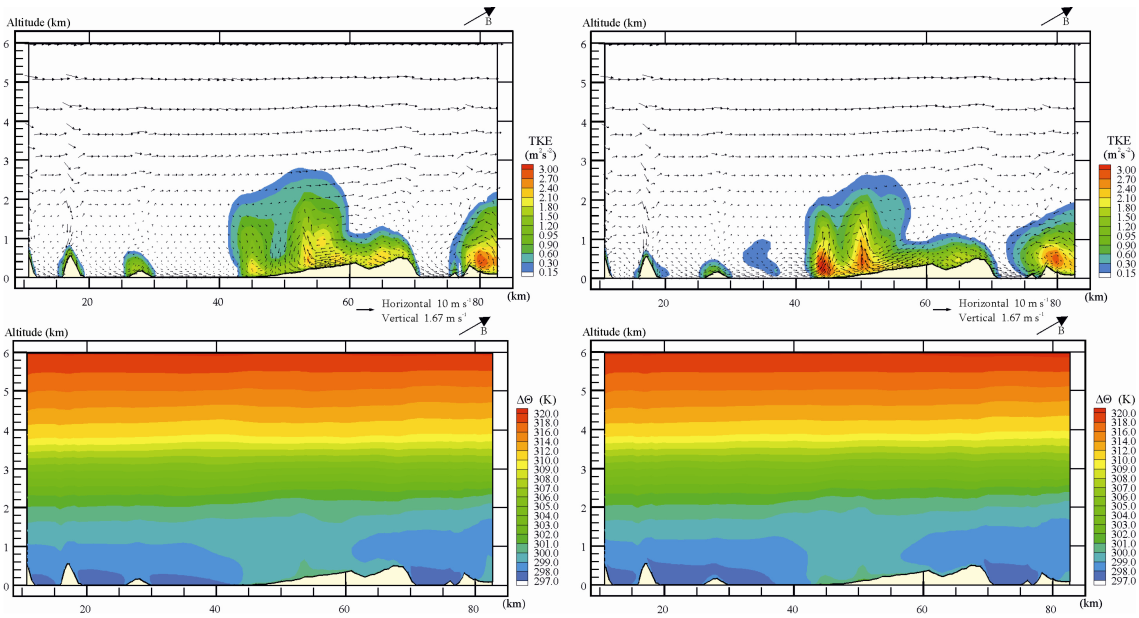

Figure 2. Vertical sections of TKE (top) and potential temperature (bottom) calculated for 20/9/2002 12:00 LST with the A1 (left) and B1 (right) model configurations. The section plane is parallel to the NNE-SSW direction.

In Figure 3 the horizontal distribution of mid-day BLH in the study domain is shown, as calculated with the A1 (left) and B1 (right) model configurations. The map reveals a well-developed daytime BL structure consistent with weak anticyclonic conditions. Most of the horizontal features can be easily attributed to orographical elements or to the presence of water bodies, including the Yliki lake and the Thebes valley on the NW part of the domain. In contrast, the 7-class A1 scheme appears to reduce the BLH over the Attica plane and in particular in the Athens urban area. In this aspect, the 11-class B1 scheme seems to improve the prediction of a higher UBL at the same time reducing the predicted BLH in the rest of the Attica peninsula. This picture is consistent with the structure apparent in Figure 2, both in terms of the horizontal BLH modulation as well as the shifts of the plume boundaries caused by the low-level wind flow. Vertical TKE and temperature sections, along the same prevailing wing direction are presented in Figure 4 for the B4 and B4f (flat topography) cases. In the case of B4f, the absence of topography resulted in a very strong northern wind field for 20/9/2002, severely distorting the BLH structure. For this reason, the 19/9/2002 12:00 LST section is shown instead. Compared to the A1 and B1 configurations, the urban plume is more pronounced, as evident by the TKE and temperature maxima, and becomes more concentrated over the areas characterised by urban LU. The secondary plume in the north of the domain remains prominent. In the absence of orographical features (B4f), the latter maximum almost disappears while the main urban BL is extended northward but without any visible weakening. While some TKE production is still observed over the islands of the Saronic gulf, the corresponding structure in the potential temperature is minimised.

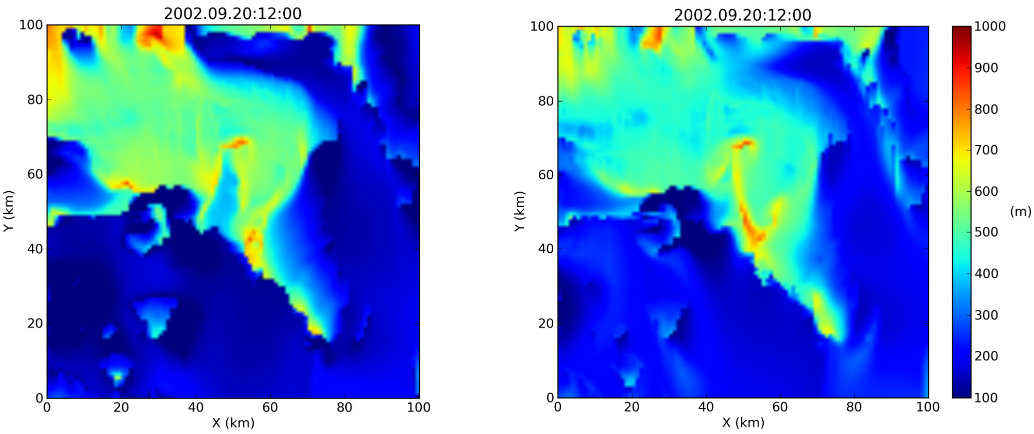

Figure 3. Spatial distribution of the simulated mixing height for 20/9/2020 12:00 LST calculated using the A1 (left) and B1 (right) model configurations

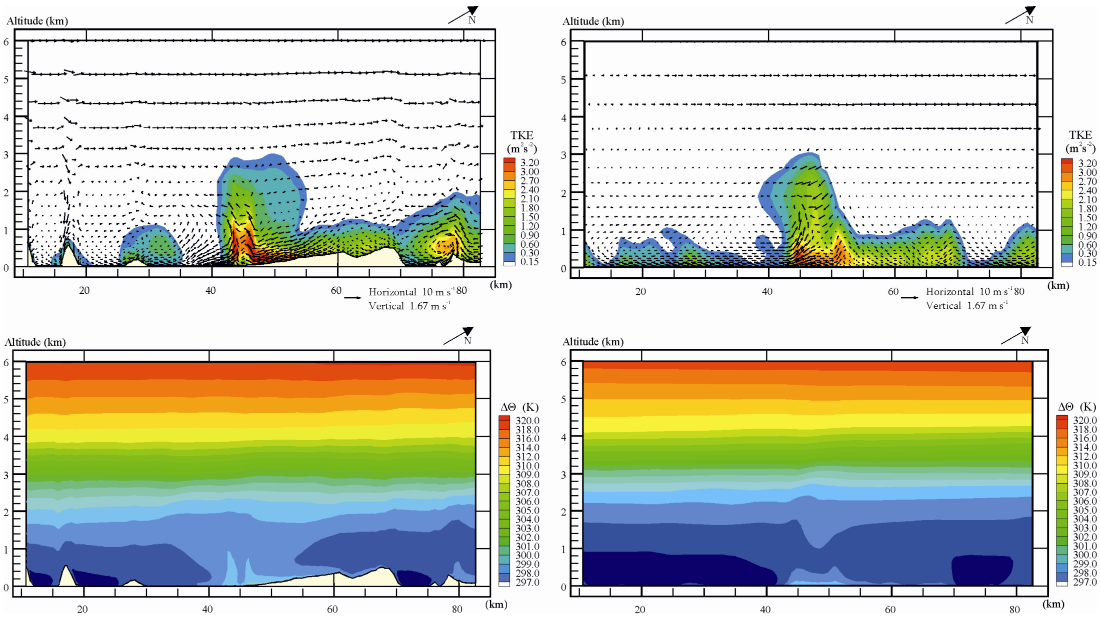

Figure 4. Vertical section of TKE (top) and potential temperature (bottom) calculated for 20/9/2002 12:00 LST with the B4 (left) and for 19/9/2002 12:00 LST with the B4f flat-topography (right) configurations. The section plane is parallel to the NNE-SSW direction.

In Figure 5 a horizontal map of the estimated mid-day BLH is shown, as calculated with the B4 and B4f model configurations. In the case of B4, the most prominent feature is the enhancement of the BL over the southern part of the Athens-Piraeus urban areas, which is consistent and spatially correlated with a corresponding increase in the estimated anthropogenic heat flux in this scheme (Nitis, 2016). The effect of the inland water bodies like Yliki on the NW is also more pronounced. The second most apparent feature is the dramatic increase of structure over the sea areas, in particular in the Saronic gulf on the south-SW parts of the domain. This enhancement can be attributed to the introduction of time-dependent diagnostic SST fields in the B4 configuration. In the case of B4f, the urban plume remains prominent at a little over 1000 m but the secondary effects of the mountain on the north of the domain are no longer visible. Isolated plumes of up to 700 m are observed over small suburban areas near the eastern coast of the Attica peninsula while the influence of the Yliki is still visible. The elimination of orographic influences has revealed a strong dependence of the BLH structure on the surface properties and in particular the urban land uses.

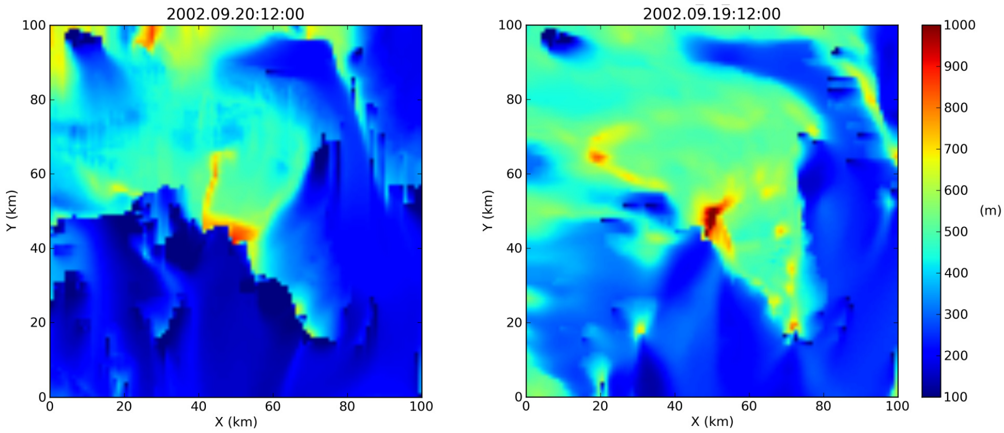

Figure 5. Spatial distribution of the simulated mixing height for 20/9/2020 12:00 LST (left) and 19/9/2020 12:00 LST (right) calculateed using the B4 and B4f model configurations, respectively

CONCLUSIONS

In this study, the non-hydrostatic mesoscale meteorological model MEMO was used to simulate the development of the urban atmospheric boundary layer in Athens, Greece with emphasis on its spatial variability and the dependence on local topographical features. A comparison between the base version and two improved model configurations, introducing a new land-surface scheme and calculation of anthropogenic heat fluxes was carried out. The thermophysical parameters of the new scheme were obtained by comparison with published values, while the sea- and land-surface temperature and albedo fields were directly derived from satellite data. In the second part of the work, the aim was to provide an insight on the effects on the mixing layer height caused by the complex topography of the Attica peninsula and the Athens urban area. To this end, a model run with a synthetic flat topography was performed. The results revealed the dominant role of the topography and SST in the development of the summertime boundary layer over Athens. At the same time, the important impact of the urban land cover and associated urban heat fluxes were revealed, in contrast to the limited impact of flux partitioning regimes associated with non-urban areas.

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