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Recent Trends and Remaining Limitations in Urban Microclimate Models

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Abstract: Problems such as natural ventilation, pollutant dispersion, changes in wind environments, and urban heat islands are gaining increasing prominence in both public concern and research. In response, urban microclimate modelling researchers are continually striving to develop new strategies to rapidly and inexpensively generate more accurate results. Numerical modelling is a common way to address these concerns. However, to generate realistic results requires significant investment in model creation, especially with respect to the detail to which a model is populated. This paper provides an overview about this and other recent trends within the research community by considering nearly 100 recent papers. Findings show that despite more computational capacity there has not been a major trend towards increasing the model complexity to obtain more realistic results.

INTRODUCTION

Due to continuing changes in land-use practices, rapid urbanization, and heightened awareness about environmental justice, concerns about environmental modelling continue to rise. For urban areas the following microclimates topics are of particular interest:

- Wind flow alteration caused by construction or demolition in the physical environment

- Air quality deterioration affiliated with contaminant transport or pollutant dispersion

- Heat distribution changes related to modifications in land usage

To control wind flow, mitigate air quality deterioration, and limit unintentional temperature changes, several strategies are being undertaken. These include promoting vegetation growth and natural ventilation, reducing traffic to decrease dispersion of ultrafine particles (UFPs), and minimizing energy consumption. To predict the effectiveness of such changes depends upon the quality of available tools to model these phenomena. Such tools require the correct governing equations and boundary conditions and implementation of appropriate numerical algorithms. Arguably they also require a relatively high level of detail of the buildings and the surrounding environment. Yet, anecdotal evidence would indicate that these factors are not regularly being considered. This paper investigates the current state of the art in computational urban microclimate models to try to quantify the

level of detail being portrayed and to describe a possible new mechanism for populating urban computational models for microclimate modelling.

SCOPE AND METHODOLOGY

To investigate the current extent to which buildings and their surrounding environments are being modelling numerically, this paper considers three topics: Wind Environment (WE), Air Quality (AQ), and Urban Heat Island (UHI). This is done through the analysis of the work of 223 authors from 22 countries through 56 internationally, peer-reviewed journal papers published from 2010 to 2013 [1-56]. Amongst these were 19 UHI papers exploring vegetation, building energy simulation, urban street characteristics, urban physics, thermal modelling, perpetual fidelity, and thermal comfort [1-19]. An additional 18 papers investigated AQ [20-37], with respect to natural ventilation, dispersion of traffic induced UFPs, contaminant transport, climate change, health in cities, ventilation strategies, micro-environments, and aerosol dynamics. Finally, there were 19 WE papers [38-56] considering the outdoor wind environment, wind flow, cross ventilation, kinetic energy, pollutant dispersion, urban morphology, surface roughness, and vegetation. These 56 papers were considered with respect to 40 earlier papers (published from 2005 to 2010) [57-96] that were previously considered by Laefer and Anwar [97] (Fig. **1**).

The percentage of papers that employed numerical modelling (as opposed to use of wind tunnels or field measurements) was similar in each study (85%). In the current study, numerical modelling was used in 94% of AQ papers, 89% of WE papers, and 72% of UHI papers. So despite arguably ever improving computing capabilities (e.g. being more user-friendly, reliable, and economical, as well as having enhanced visualization and virtual modelling options), numeri-

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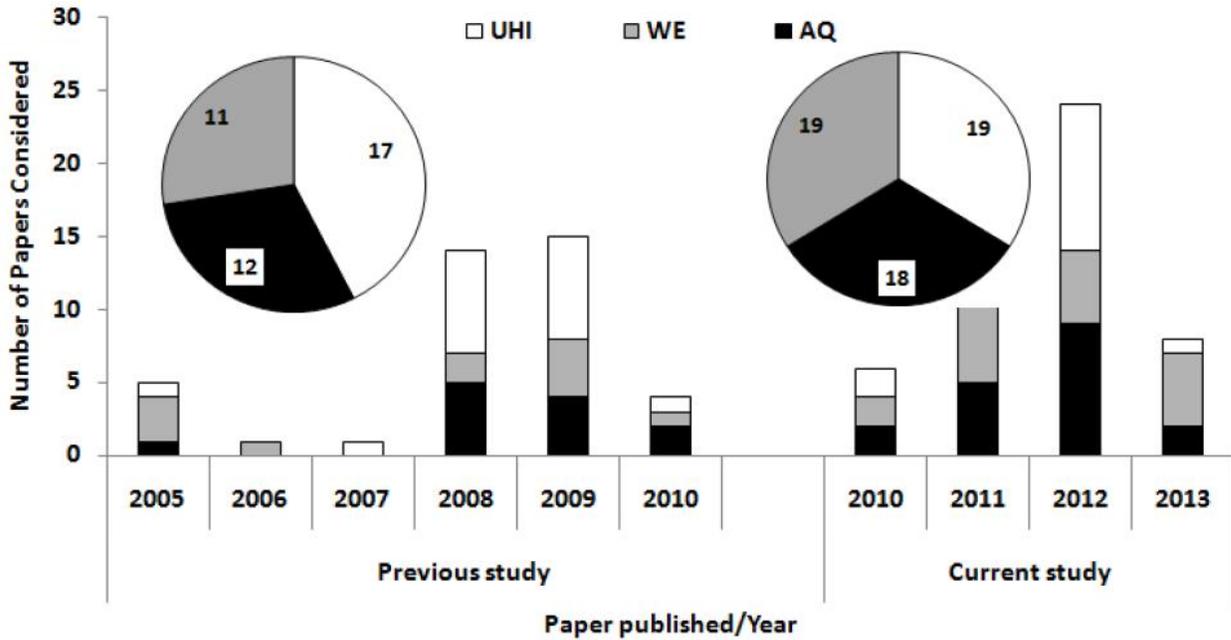
Fig. (1). Number of papers considered per year and papers per category in each study.

(**a**) Previous study   (**b**) Current study
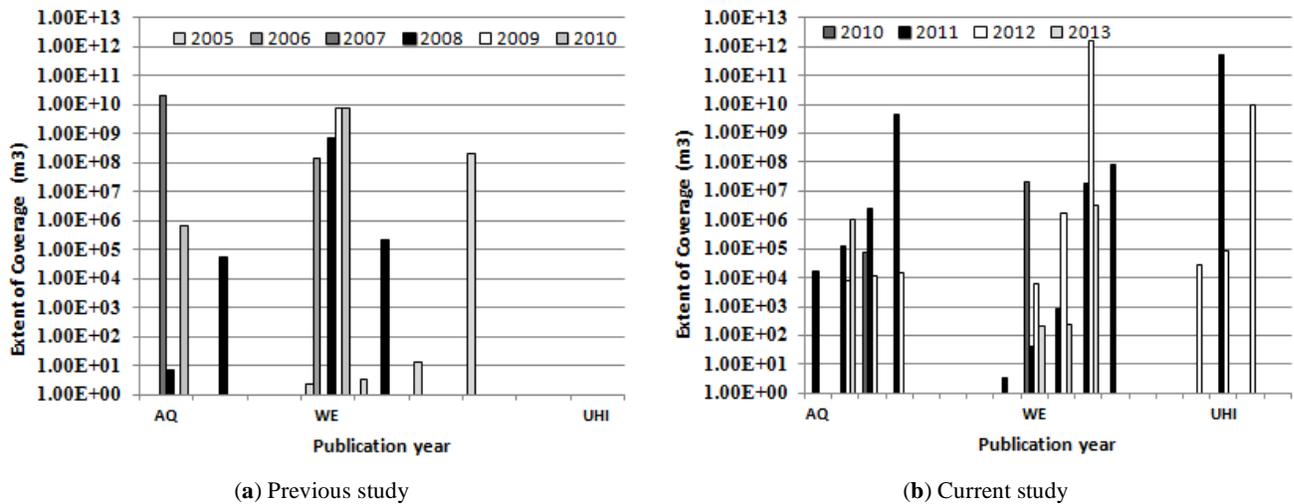
Fig. (2). Extent of coverage.

cal modelling has not fully displaced physical or analytical modelling. To investigate these and other trends, this paper considers the following topics: the physical representation, the computational representation (when applicable), and the software and algorithms in use.

PHYSICAL REPRESENTATION

The physical representation involves the model's coverage area, scale, aspect ratio, quantity of included buildings, use of an actual or hypothetical site, and dimension [three-dimensional (3D) versus two-dimensional (2D)], as well as feature set selection for model inclusion.

The study area varied from the micro-scale (0.1-10 km^2) to the macro-scale (>10,0000 km^2) (Fig. **2**). One change from the early work is that most current UHI investigations

consider the effects of urban areas on nearby suburban areas; previously the geographic extent was not considerd explicitly in UHI modelling.

In the 2010 to 2013 papers, the study area composition ranged from a single building to an entire town. While examples of multi-building inclusion continued, (Fig. **3**) depicts a clear trend to include fewer buildings (all 2012 papers included only a single building). What did not change significantly was the use of real locations, as opposed to hypothetical ones (64% in the new research papers, as opposed to 60% in papers from 2005 to 2010). The aspect ratio (building height versus street width) varied from 0.125 [46] to 1.25 [34]. While the scale varied from 1:1 to 1:5000, the mean scale was 777.87 (with a standard deviation of 1718.16). This was slightly smaller than the 1:1000 in the earlier group of papers [97].
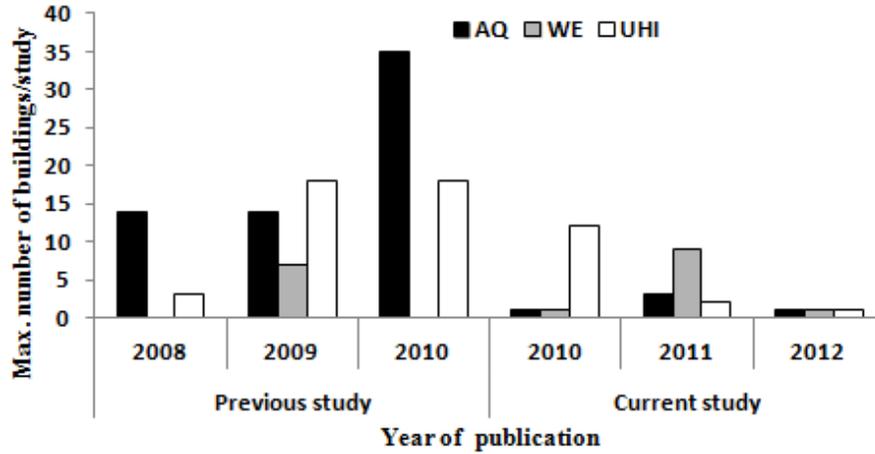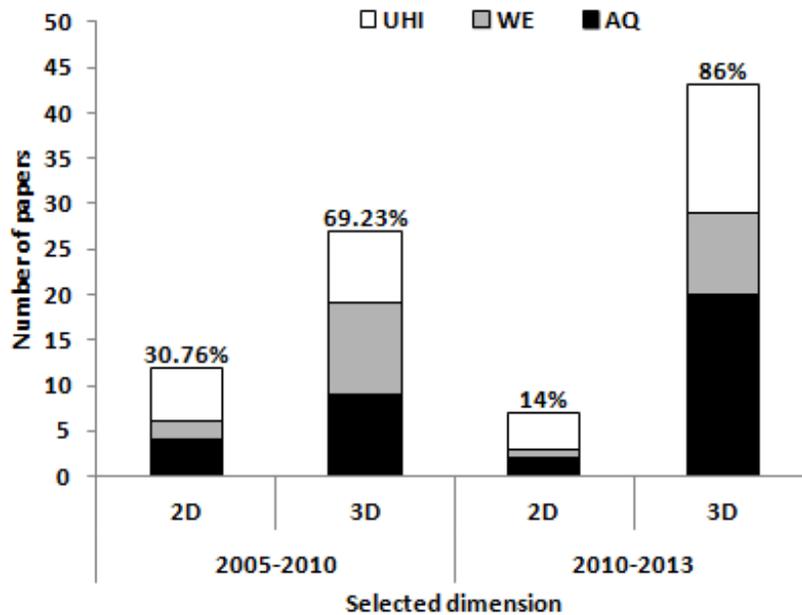
Fig. (3). Number of buildings per study.

Fig. (4). Selected dimension.

Fig. (**4**) depicts a growing trend in using a 3D domain versus a 2D one (86% *vs.* 69%). Arguably a 3D domain generates more accurate results, despite being computationally more complex and more expensive to populate, with respect to depicting the geometry of the environment. The trend may also be indicative of the increasing availability of 3D remote sensing data with better vertical resolution [98], even though such datasets are only collections of randomly distributed 3D points and do not explicitly contain topological, shape, or size information of the geographical features.

A topic of high interest is the level of detailed included in the models, as that level can impact the output quality, as shown by Li [48], who investigated medium rise buildings with and without balconies for predicting mean wind pressure distribution on windward and leeward surfaces. While the inclusion of such elements has grown significantly (from 0.5% to 10.7%), the overall level remains modest, and many features of the built environment such as footpaths, curbs, and steps have never been considered (Table **1**). A similar increased level of inclusion occurred for vegetation (from 1.2% to 14.8%) or building disposition (only [22]), despite natural ventilation being one of the most fundamental way to reduce building energy usage [4, 34]. Another advance is the increased inclusion of vehicle emissions (0.2% *vs.* 8.51%) to better predict turbulent transport phenomena of air-borne pollutants in built-up areas. So while the overall trends are to increase the realism in the modelling, the adoption levels remain extremely low.

THE COMPUTATIONAL REPRESENTATION

Irrespective of specific content choices, the computational representation of a micro-climate model involves significant grid-related information (e.g. geometric shape and

Table 1. Details of modelled elements (shown as a percentage of the papers considered).

Modelled Elements	40 Papers (2005-2010)	56 Papers (2010-2013)
Vegetation	1.2%	14.8%
Signage	NIM	NIM
Street Furniture	NIM	NIM
Steps	NIM	NIM
Curbs	NIM	NIM
Footpath	0.5%	2.1%
Texture	1%	NIM
Setbacks	0.2%	6.3%
Balconies	NIM	2.1%
Other Decorative Elements	0.5%	10.7%
Windows	0.2%	2.1%
Vehicles Emissions	0.2%	8.51%

NIM[*]- Not included in model

(**a**) Structured   (**b**) Unstructured
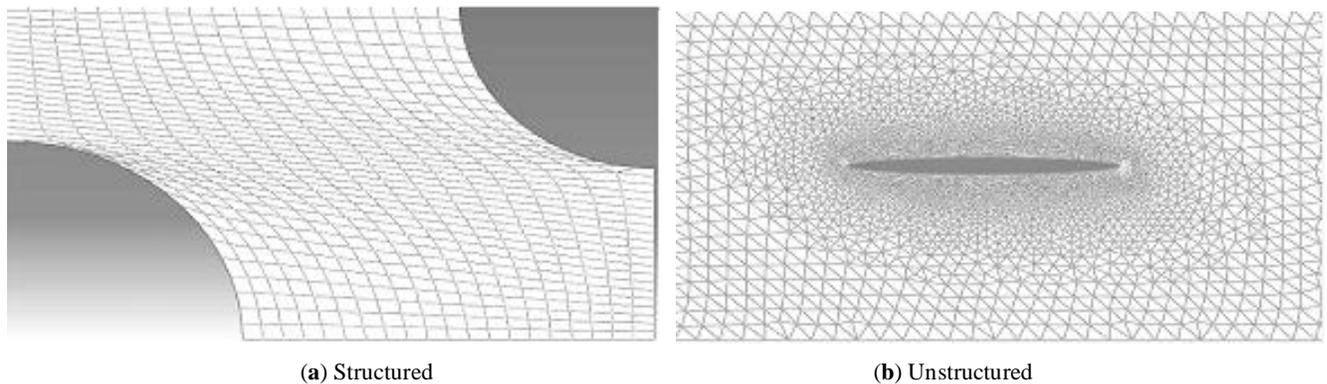
Fig. (5). Geometry of elements.

types, dimensionality, generation technique and population strategy, as well as convergence criteria).

A grid is the arrangement of discrete points/elements over the flow field. Grid generation is the determination of the proper grid for the flow around a given geometric shape. Grids are considered either structured (Fig. **5a**) or unstructured (Fig. **5b**). Structured grids are generally composed of a regular arrangement of quadrilateral (2D) or hexahedral (3D) elements, while unstructured grids often use triangular (2D) or tetrahedral (3D) elements and can be created automatically for almost any geometry by means of tessellation [99]. While there was no dominance in micro-climate modelling for structured versus unstructured grids, a strong preference (almost 3 to 1) was apparent for the use of 3D elements over 2D elements, despite the related need for more complex calculations for the 3D elements (Table **2**).

Generally, one of two different grid generation techniques is applied: (1) the body-fitted or conforming method, or (2) the immersed-boundary method. The most common is the body-fitted method, where the external mesh face conforms to the surfaces [i.e. the external mesh face matches the surface (body surface and/or external surface) (Fig. **6a**)]. Usually, a body conforming grid is used for computing the flow around an arbitrary body. This approach requires coordinate transformations and/or complex grid generation. If the body-fitted method is applied to moving bodies, a new mesh must be generated for each time step, which requires significant computing time.

An alternative is the immersed body method (also known as the embedded mesh Cartesian method) (Fig. **6b**). The main idea is to place bodies inside the flow region within a large mesh. In this method, the external mesh surface does not fully match the body surface. Hence, the mesh does not need to move. The distinguishing feature of the immersed boundary method is that the entire simulation can be conducted on a Cartesian grid. In such cases, the solid boundary

Table 2. Selection of numerical elements used in studies.

Element Type	Freq. of Usage for Group 1 Papers 2005-2010	Freq. of Usage for Group 2 Papers 2010-2013	Dimension
Hexahedral	3	6	3D
Tetrahedral	2	5	3D
Prismatic	1	3	3D
Irregular	2	0	3D
Triangular	3	1	2D
Quadrilateral	1	0	2D
Rectangular	1	2	2D
Unspecified or non-applicable	27	39	
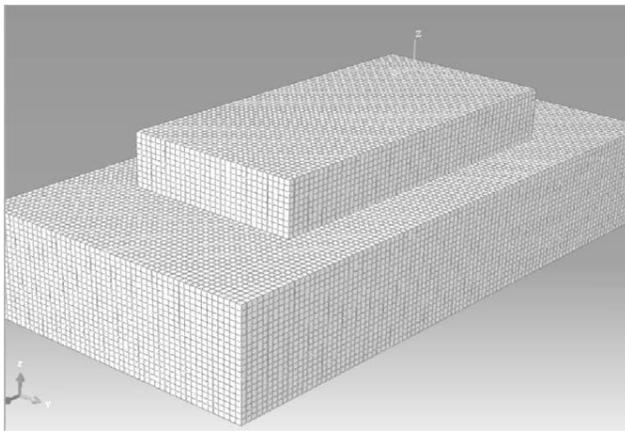
(**a**) Body-fitted grid
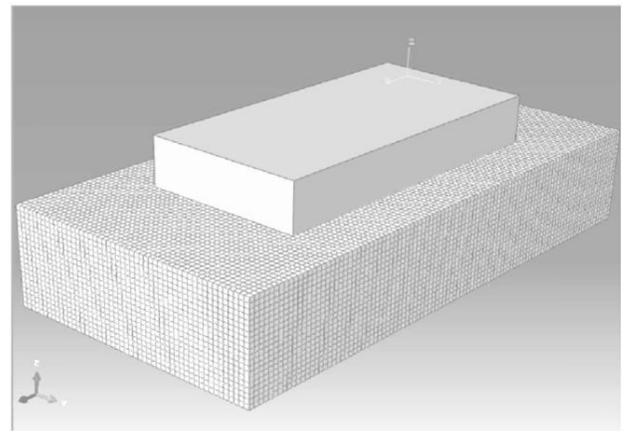
(**b**) Immersed boundary grid

Fig. (6). Grid generation techniques.

cuts through the grid. Because the grid does not conform to the solid boundary, imposing boundary conditions requires modifying the governing equations in the vicinity of the boundary. This method applies to the treatment of problems with (1) dirty geometry, (2) moving bodies with thin gaps, and (3) those with laminar flow [99]. While the immersed-boundary method has the advantage of being simple, thereby minimizing CPU and memory requirements without compromising the accuracy, it still exhibits many shortcomings, as identified in references [99-101].

- Approximations occur at boundaries.

- Near the boundaries, the embedding boundary conditions need to be applied, which may reduce the local order of approximation for the partial differential equations.

- Mesh adaptivity is essential for most cases.

- Considerable time is required to build the proper boundary conditions for elements close to the surface or inside bodies for moving boundaries.

- Obtaining the information required to transfer forces back to the structural surface can be time consuming for fluid–structure interaction problems.

Irrespective of element geometry, element type, or grid generation type, several user-defined inputs are needed. One is the mesh density. The number of grids required for a mesh depends upon the complexity of the object. The inclusion of more grids generates more accurate results but adversely increases the computer runtime. In the papers considered, grid population varied from 1.00E+05 to +09, without any discernible trends between the data sets (Fig. **7**).

Another user-defined parameter relates to convergence. The convergence level can control the processing duration. Higher values may decrease runtimes but may lead to possible instabilities. Conversely, lower values may further increase stability at the expense of longer runtimes. Numerical methods used to solve the equations for fluid flow and heat transfer most often employ multiple iterations, thus requiring convergence criteria. In many cases, iterative methods are supplemented with relaxation techniques. For example, over-relaxation is often used to accelerate the convergence of pressure-velocity iteration methods, which are needed to satisfy an incompressible flow condition. Under-relaxation is sometimes used to achieve numerically stable results when all the flow equations are implicitly coupled. Selecting proper relaxation and convergence criteria can be difficult. The convergence criteria depends on the specifics of the
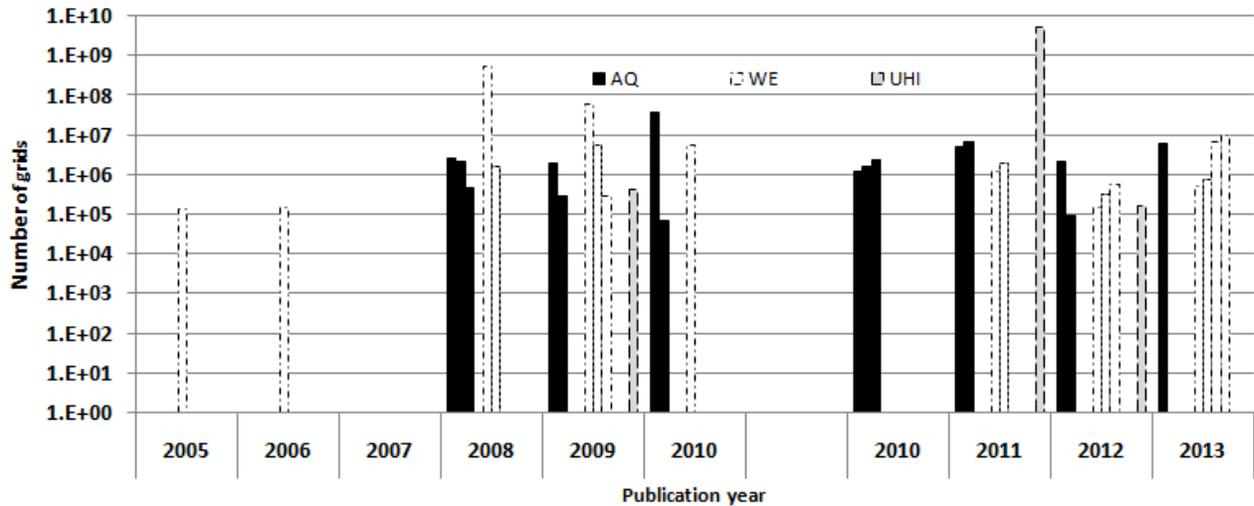
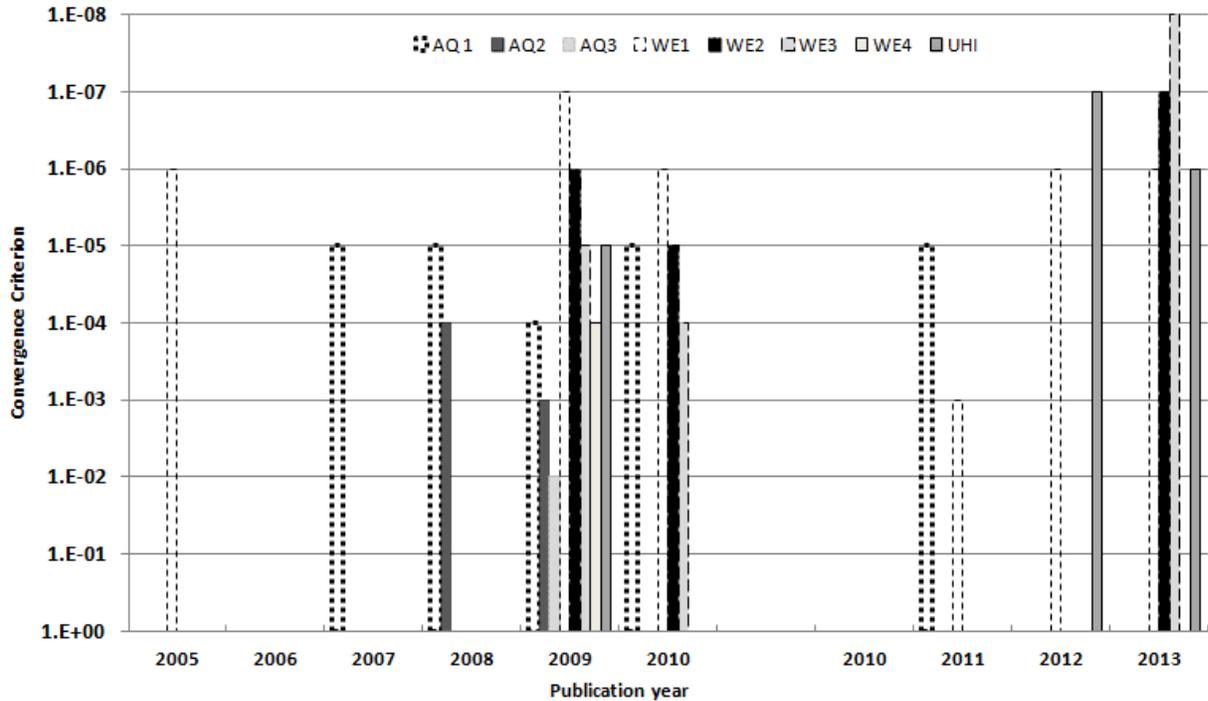**Fig. (7).** Number of grids employed per study.

Fig. (8). Convergence criterion.

problem being solved, which may change during the evaluation of a problem. There are no universal guidelines for selecting criteria because they depend not only on the physical processes but also on the detail of the numerical formulation. Across the 96 papers, the convergence criterion varied from IE-4 to IE-7, thereby showing no discernible trends.

MODEL AND SOFTWARE SELECTION

The final topic area for consideration in this paper relates to model and software selection, which depends upon the problem's complexity level, nature, and required accuracy of the results, as well as the project's resources. As shown in (Fig. **8**), the Reynolds Averaged Navier-Stokes (RANS) approach forms the basis of a large number of the implemented models. RANS can address all scales of turbulence, is considered easy to implement, and is computationally inexpensive. Thus, its popularity persists despite its poor performance in cases of large adverse pressure gradients and its restriction to usage in only fully developed turbulent and non-separated flows [102]. The next most popular choice is the large eddy simulation method (LES). LES is a filtered
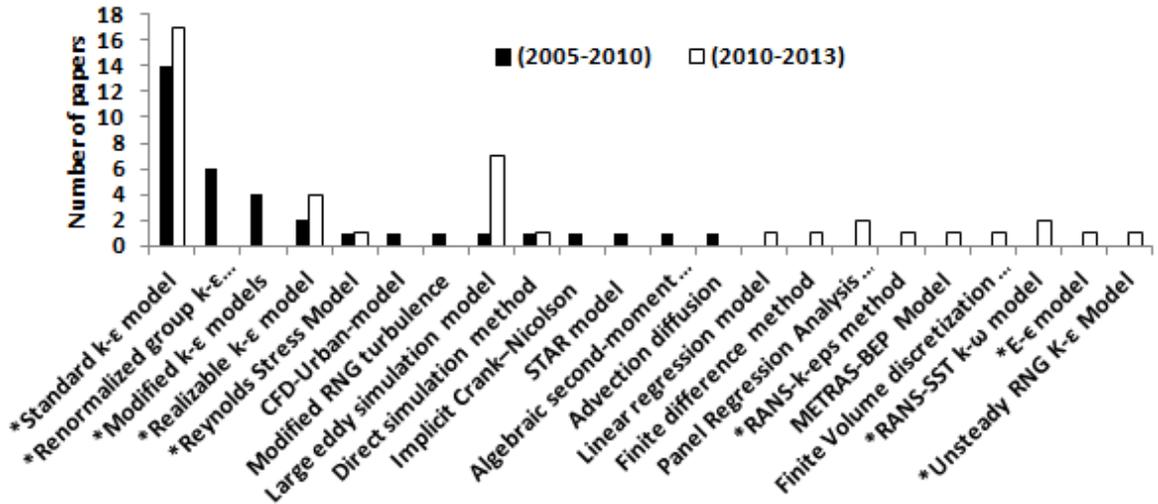
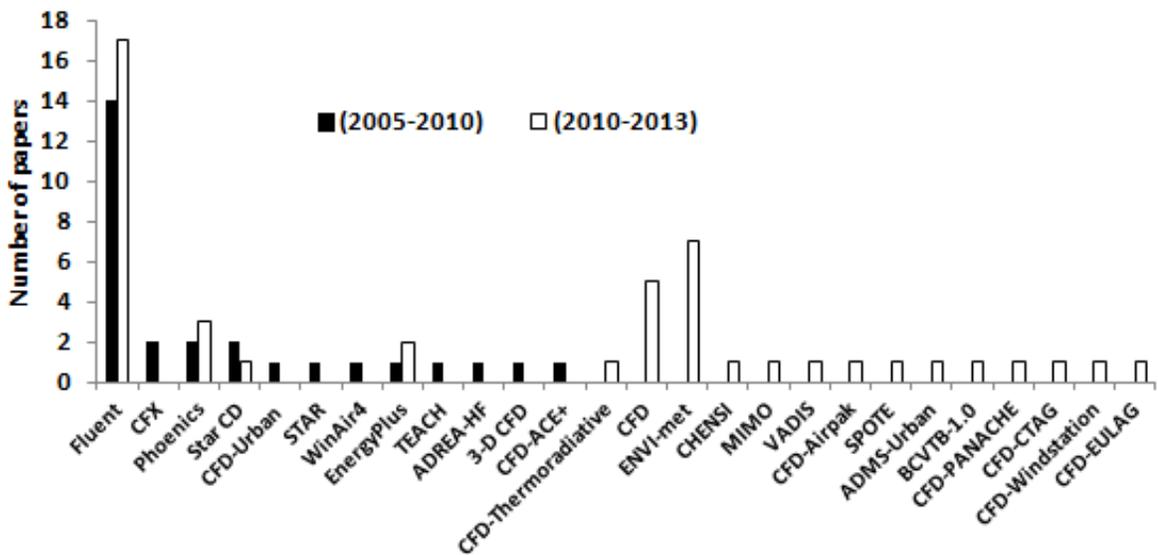**Fig. (9).** Implemented models (*denotes a RANS-based model).


Fig. (10). Selected software.

version of the Navier-Stokes Equations, along with another equation to represent small-scale turbulence. Although more computationally expensive, LES produces more accurate and reliable results, because it resolves the turbulent mixing process in the flow field [53]. Over the past three years, LES has gained in popularity, while usage of the renormalized and modified k-ε models has lessened across the entire study set (Fig. **9**). The vast majority of specific models were only used once indicating a continued amount of significant development in this area.

Amongst the available commercial software, FLUENT dominates usage (Fig. **10**) and is the CFD solver of choice for complex flows ranging from incompressible (low subsonic) and mildly compressible (transonic) ones to highly compressible (supersonic and hypersonic) flows. By providing multiple choices for solver options. FLUENT is applicable to a wide range of engineering problems both laminar and turbulent, for various heat transfer modes, chemical reactions, and multi-phase flows. Notably, there is a growing

trend to use ENVI-met: a 3D, numerical microclimate model mainly for air quality that uses a Eulerian approach for calculation of mass, momentum, and an energy budget [34]. ENVI-met is based on a RANS equations, with a non-hydrostatic, micro-scale, obstacle-resolving model and advanced parameterizations for simulation of surface-plant-air interactions in urban environments [103]. ENVI-met provides both spatial resolution (0.5-10 m) and temporal variation (finest 10 s resolution) for an urban boundary layer climate. Additionally, ENVI-met has features not commonly available in other CFD dispersion codes (e.g. a detailed microclimate module and a vegetation module). The required input includes meteorological data, emissions, and domain characteristics [32].

NEW DEVELOPMENTS

Two other new developments were noted that may have a large impact on future modelling. The first was the usage of

a) Single pass aerial laser scan   **b**) Multi-pass aerial laser scan
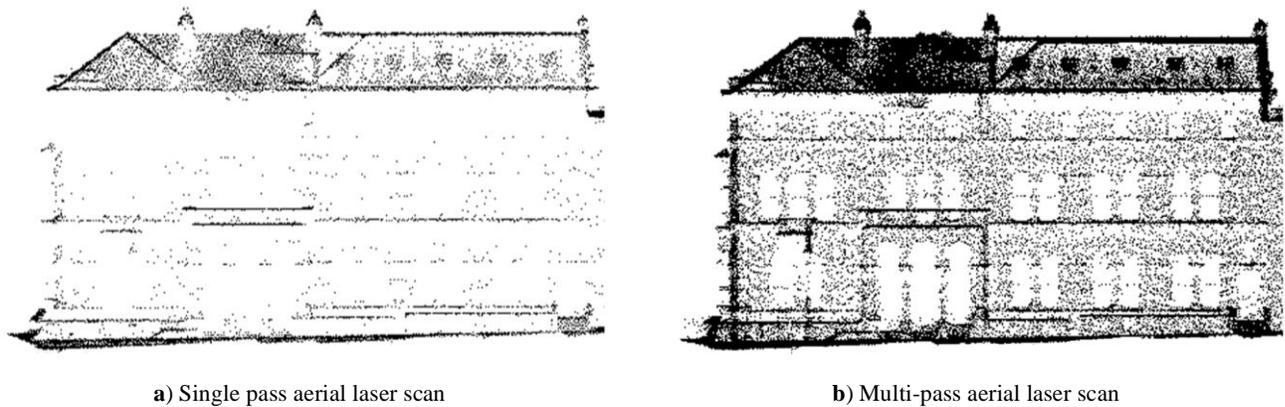
Fig. (11). Example of current vertical façade data density from aerial laser scanning.

Comprehensive Turbulent Aerosol dynamics and Gas chemistry (CTAG), also called CFD-Vehicle Induced Turbulence (VIT) or CFD-Road Induced Turbulence (RIT). CTAG is a computational fluid dynamics based, turbulent-reaction, flow model to estimate the spatial and temporal impacts of multiple air pollutants from traffic-related emissions for people living near major roads. The approach explicitly couples the major turbulent mixing processes VIT/RIT and atmospheric boundary layer turbulence) with gas-phase chemistry and aerosol dynamics. Aerosol dynamic processes such as nucleation, coagulation, condensation, and evaporation are coupled with turbulent mixing to govern the evolution of exhaust particles. Gas phase chemical reactions also couple with turbulent mixing [36]. A novel multi-scale structure is created to advance the capability of simulating the evolution of UFP's from vehicular tailpipes to near road environment. A multiple scale is implemented in the CTAG model to characterize the micro-environmental air quality near highways. The authors of reference [35] note that CTAG is still computationally expensive compared to parameterized dispersion models, although specific figures were not provided.

The second trend is perceptual fidelity, the idea of introducing sound to reproduce the physical stimuli in microclimatic and multisensory urban environments. Arguably, the main focus to date on visual aspects restricts understanding, since multisensory ambiances are significant [102, 104]. Namely, the concept of sonic effect describes the interaction between (1) the physical sound environment, (2) the sound milieu of a socio-cultural community, and (3) the "internal soundscape" of each individual.

DISCUSSION

While more CFD models are including a greater level of detail, there is also a trend to include less of the surrounding structures. One possible explanation is that the extra effort being invested in representing the details of the main structure is consuming resources that are not available for the creation of nearby geometries. If this is the case, one possible solution is the use of aerial laser scanning or other remote sensing technology to represent some or all of the surrounding area. There are however several challenges to this.

While alternative flight paths with multiple overlaps, such as those proposed by Hinks *et al.* [98] can greatly improve the vertical resolution of data capture (Fig. **11a** *vs.* **11b**), and direct conversion methods are available to transform the points into an appropriate solid model [105], approaches for segmentation (Fig. **12**) and automated feature identification (two required tasks that provide the path between the data capture and the computational model) are not sufficiently robust at a city-scale. Consequently the resulting geometries will not be very accurate without significant manual intervention. However, given the current trend to excluding nearby built elements can be offset by the inclusion of these less than perfect automated models.

CONCLUSION

In this survey of nearly 100 micro-climate modelling papers over the past eight years several trends were noted:

1. The inclusion of fewer buildings (and often only one building), but with a higher level of detail (especially vegetation and vehicle emissions), at a 25% smaller scale, and with a greater propensity of using more actual sites (as opposed to hypothetical locations).

2. A greater usage of three-dimensional aspects (as opposed to two-dimensional ones) in both the domain and in the choice of elements.

3. A growing trend for the Large Eddy Simulation method and ENVI-met software, despite a continuing dominance of RANS-based methods and the software Fluent.

While the latter two trends represent clear advances in the field, the first is not definitively so and raises the question as to why the higher detailing of buildings seems to be in parallel with the exclusion of surrounding structures. Certainly, the justification for omitting surrounding structures is regularly excluded from recently published literature. What appears to be missing is a clear set of guidelines for research as to the extent of surrounding obstacles that should be included for the adequate modelling of the three cases of wind, urban heat, and pollution dispersion.
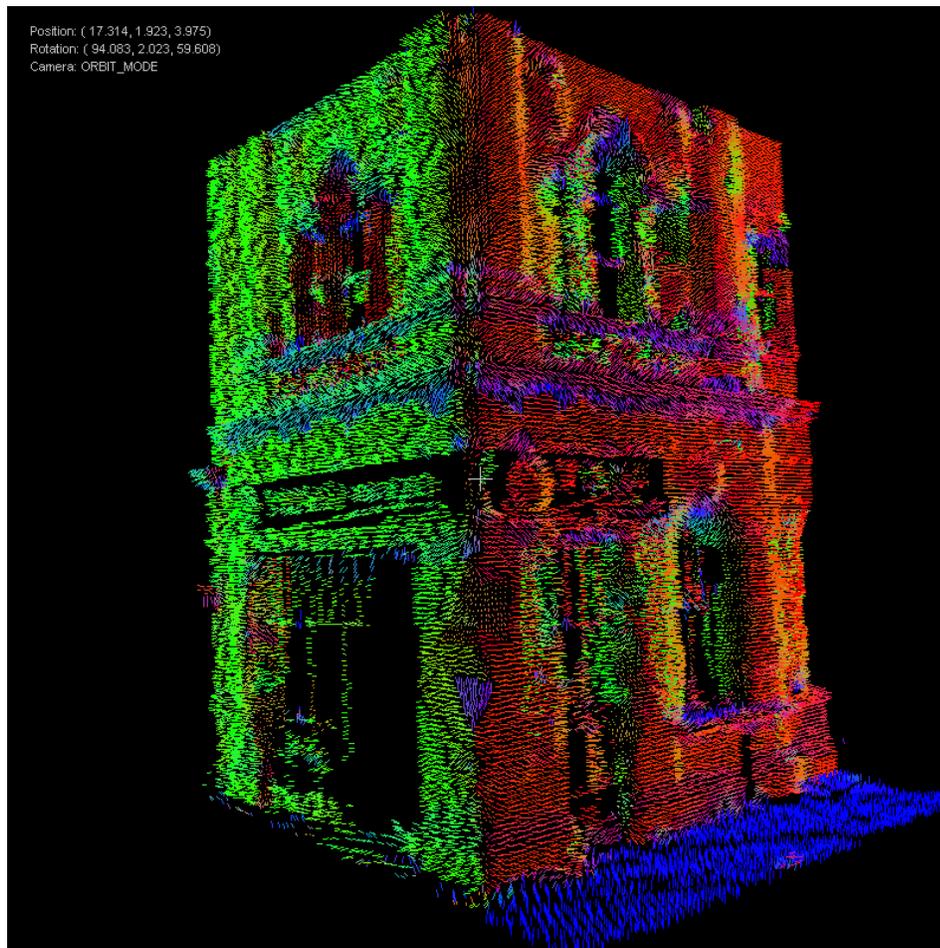
Fig. (12). Example of segmentation of aerial laser scanning data for subsequent use in a computational model.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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