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Recent Trends and Remaining Limitations in Urban Microclimate Models

Manmeet Singh and Dr. Debra F. Laefer

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 from 2010-2013. Major trends related to Comprehensive Turbulent Aerosol dynamics and Gas chemistry (CTAG) and perceptual fidelity.

Keywords: Microclimate, Wind Environment, Air Quality, Urban Heat Island, Computational Fluid Dynamics, Perceptual Fidelity, Comprehensive Turbulent Aerosol dynamics and Gas chemistry, Environmental Justice

INTRODUCTION

Due to continuing changes in land-use practices, rapid urbanization, and heightened awareness about environmental justice, concerns about environmental modelling is on the rise. For microclimates the following topics tend to be 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 the deterioration of air quality, and limit unintentional temperature changes in urban areas, 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. Selection of each depends upon the specific problem.

As such, this paper investigates the current state of modelling for three problems: 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 addition 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 papers (published from 2005 to 2010) [57-96] previously considered by Laefer and Anwar [98]. In both studies, topic distribution of the papers was similar (Fig. 1).

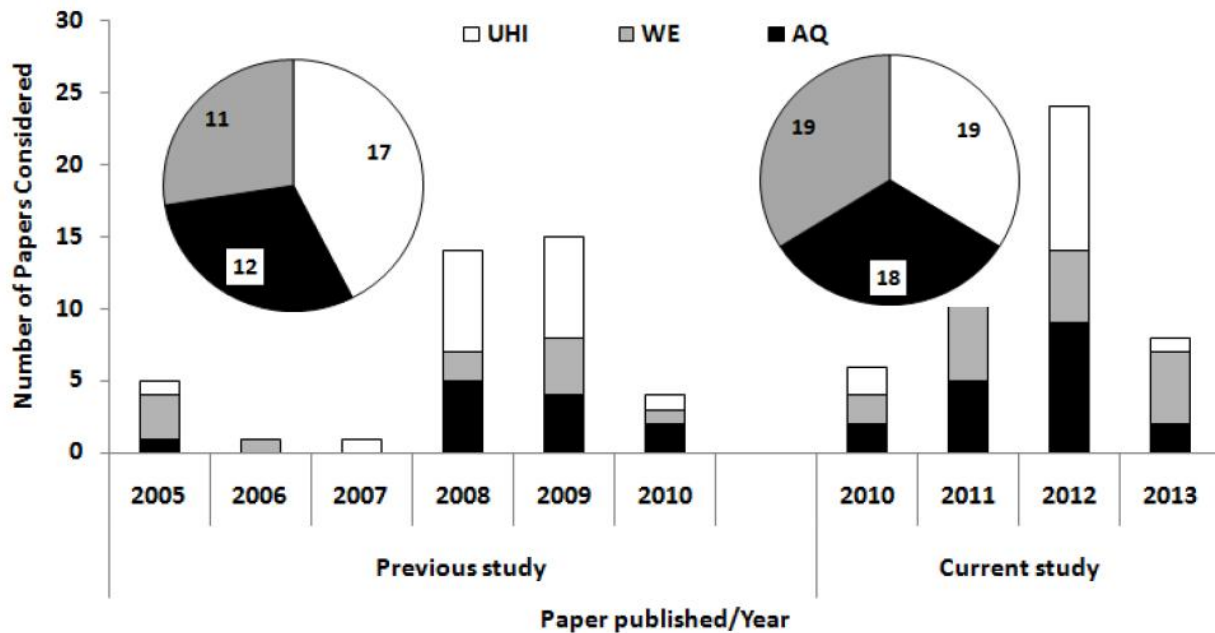


Figure 1. Number of papers considered per year and papers per category in each study.

Research Approach

Interestingly, the percentage of papers that employed numerical modelling was similar in each study (85% currently versus 85% previously). In the current study, numerical modelling represented 94% AQ papers, 89% WE papers, and 72% of UHI papers. This reflects a growth in numerical modelling of 2% in AQ and a 13% growth in WE but a 13% reduction in UHI. 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), numerical 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.

The 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)]. Feature set selection for model inclusion is also considered.

The study area varied from the micro-scale (0.1-10 km²) to the macro-scale (>10,000 km²) (Figure 2). Current research limits the extent to the meso-scale level (10-200 km²). Notably, prior to the year 2010, the geographic extent was not considered explicitly in UHI modelling. Most current UHI work considers the effects of urban areas on nearby suburban areas.



Figure 2. Extent of Coverage

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. Figure 3 depicts a clear trend to include fewer buildings; in fact all 2012 papers used only a single building. Additionally, there is a small move towards greater locality realism. From 2010 to 2013, 64% of papers used real locations as compared to 60% from 2005 to 2010, as opposed to hypothetical ones. The aspect ratio (building height versus street width) varied from 0.125 [46] to 1.25 [34]. The scale used varied from 1:1 to 1:5000. The mean scale was 777.87 (with a standard deviation of 1718.16), as compared to 1:1000 in the previous set [98].

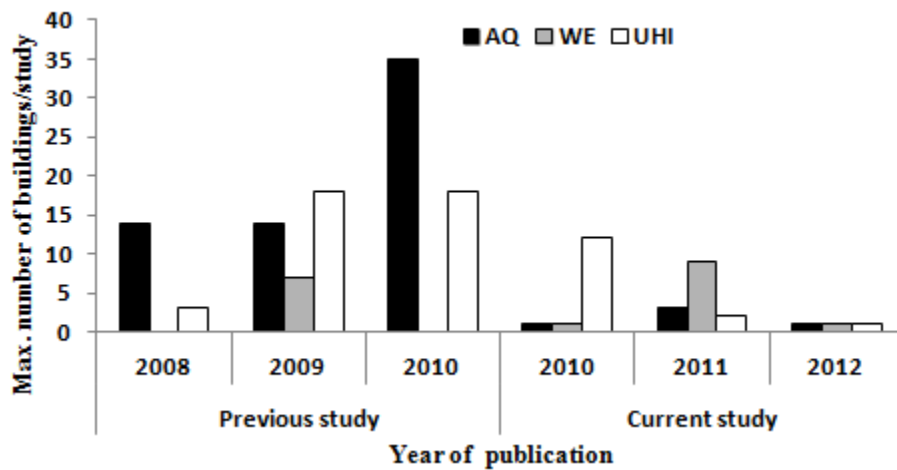


Figure 3. Number of buildings per study

Figure 4 depicts a growing trend to use a 3D domain versus a 2D one (86% vs 69%). Arguably a 3D domain generates more accurate results, despite being computationally more expensive and complex. The trend may also be indicative of the increasing availability of 3D remote sensing data with better vertical resolution [99], 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.

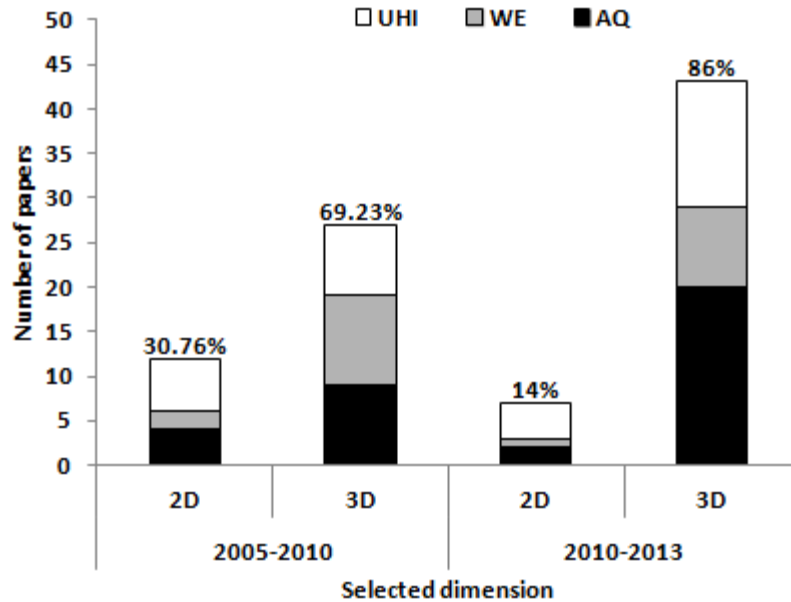


Figure 4. Selected dimension

The elements that are included in a model can impact the analysis outputs. For example, Li [48] investigated medium rise buildings with and without balconies for predicting mean wind pressure distribution on windward and leeward surfaces. Inclusion of such elements is slowly growing (Table 1). For instance, the inclusion of architectural elements has also greatly increased between the two study sets (0.5% vs 10.7%), the overall level remains modest and many features of the built environment such as footpaths, curbs, steps have never been considered (Table 1). A more notable increase has been in the inclusion of vegetation (1.2% vs 14.8%), but the total percentage still remains relatively low considering its known importance. Furthermore, even though natural ventilation is the most fundamental way to reduce energy usage in buildings [4,34], few studies include building disposition (e.g. [22]). Vehicle emission inclusion has also increased substantially from 0.2% in the years 2005-10 to 8.51% in the years 2010-13. This is logical since prediction of turbulent transport phenomena of air-borne pollutants in built-up areas requires a complex obstacle resolving type of dispersion model.

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

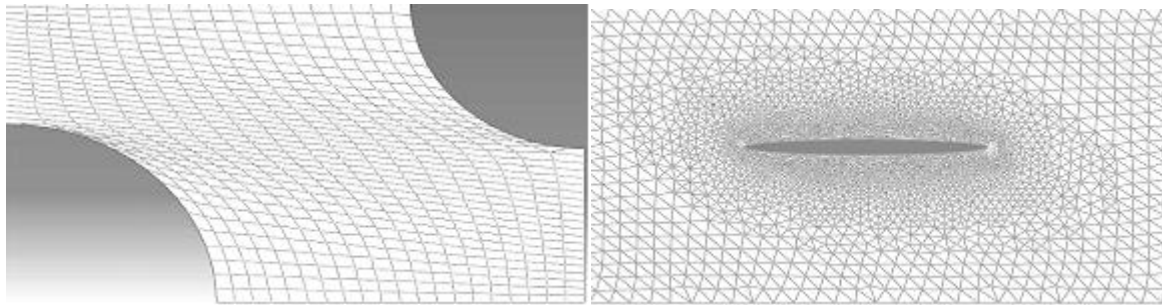
Modelled Elements	40 papers (2005-2010)	56 papers (2010-2013)
Vegetation	1.2%	14.8%
Signage	NIM	NIM
Street Furniture	NIM	NIM
Steps	NIM	NIM
Curbs	NIM	NIM
Footpath	0.5%	2.1%
Texture	1%	NIM
Setbacks	0.2%	6.3%
Balconies	NIM	2.1%
Other Decorative Elements	0.5%	10.7%
Windows	0.2%	2.1%
Vehicles Emissions	0.2%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

NIM* - Not included in model

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 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 of a structured (fig. 5a) or unstructured (fig. 5b) type. Structured grids are generally composed of a regular arrangement of quadrilateral (2D) or hexahedral (3D) elements, while unstructured grids are often triangular (2D) or tetrahedral (3D) elements. Unstructured grids can be created automatically for almost any geometry by means of tessellation [101]. 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).



(a) Structured

(b) Unstructured

Figure 5. Geometry of elements

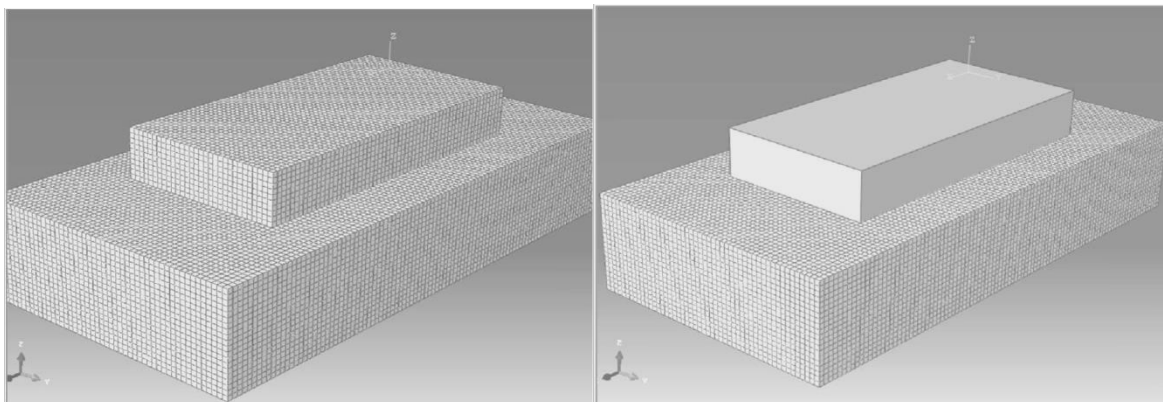
Table 2. Selection of numerical elements used in studies

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	

Generally, one of two different grid generation techniques is applied: the body-fitted or conforming method or the immersed-boundary method. The most common is the body-fitted method, where the external mesh face conforms to the surfaces [i.e. where 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 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 [100]. While the immersed-boundary method has the advantage of being simple and minimizing CPU and memory requirements without compromising the accuracy, it still exhibits many shortcomings, as identified by [100-102].

- Approximations occur at boundaries
- Near the boundary, the embedding boundary conditions need to be applied, which in many cases reduces the local order of approximation for the partial differential equations
- Mesh adaptivity is essential for most cases
- Problems with moving boundaries require considerable time to build the proper boundary conditions for elements close to the surface or inside bodies
- For fluid–structure interaction problems, obtaining the information required to transfer forces back to the structural surface can be time consuming.



(a) Body-fitted grid

(b) Immersed boundary grid

Figure 6. Grid generation techniques

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 run time. In the papers considered, grid population varied from $1.00E+05$ to $+09$, without any discernible trends between the data sets (fig. 7).

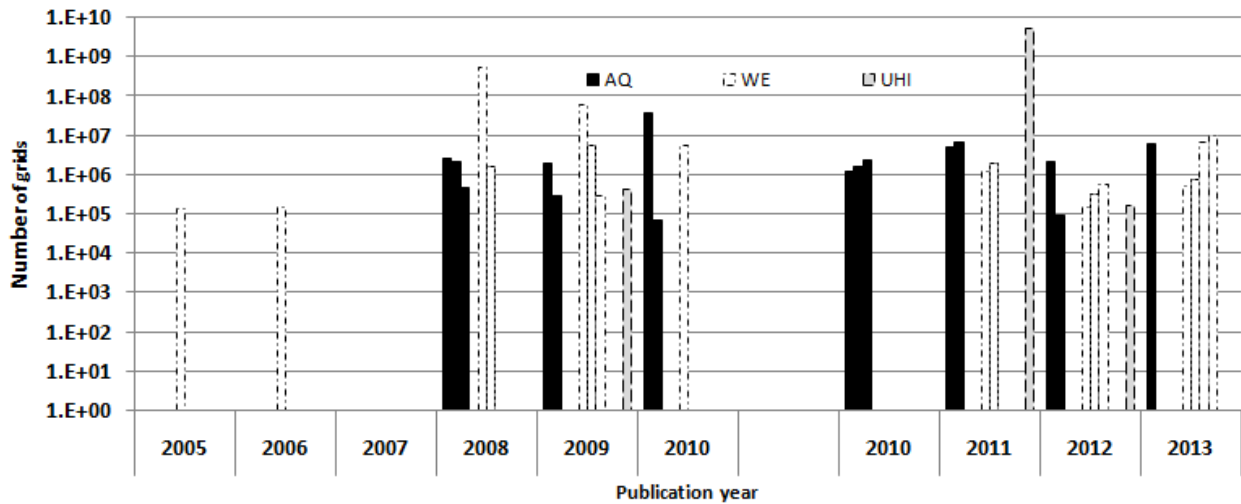


Figure 7. Number of grids employed per study

Another user-defined parameter related to convergence. The convergence level can control the processing duration. Higher values may decrease runtimes but 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 criterion can be difficult. The convergence criterion depends on the specific of the problem being solved, which may change during the evaluation of a problem, but 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 $1E-4$ to $1E-7$, with no discernible trend.

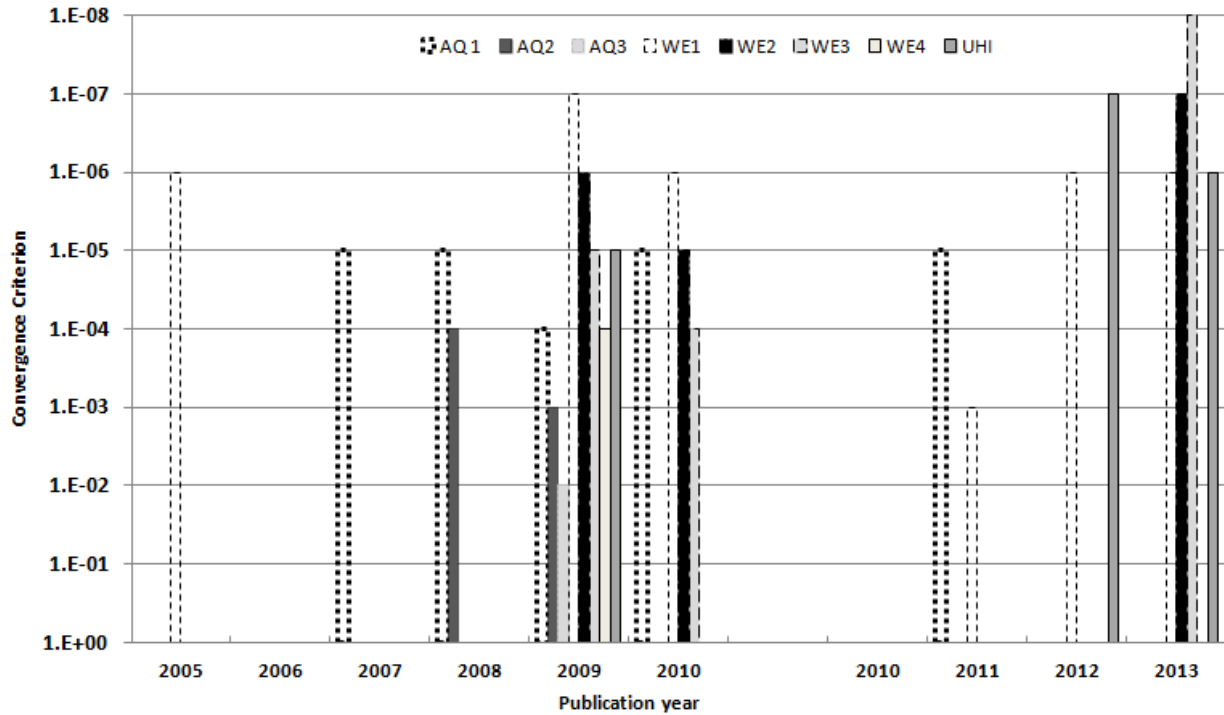


Figure 8. Convergence criterion

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 Figure 9, 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 [103]. The next most popular choice is the large eddy simulation method (LES). LES is a filtered 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 $k-\epsilon$ models has lessened across the entire study set (Figure 9). The vast majority of specific models were only used once indicating a continued amount of significant development in this area.

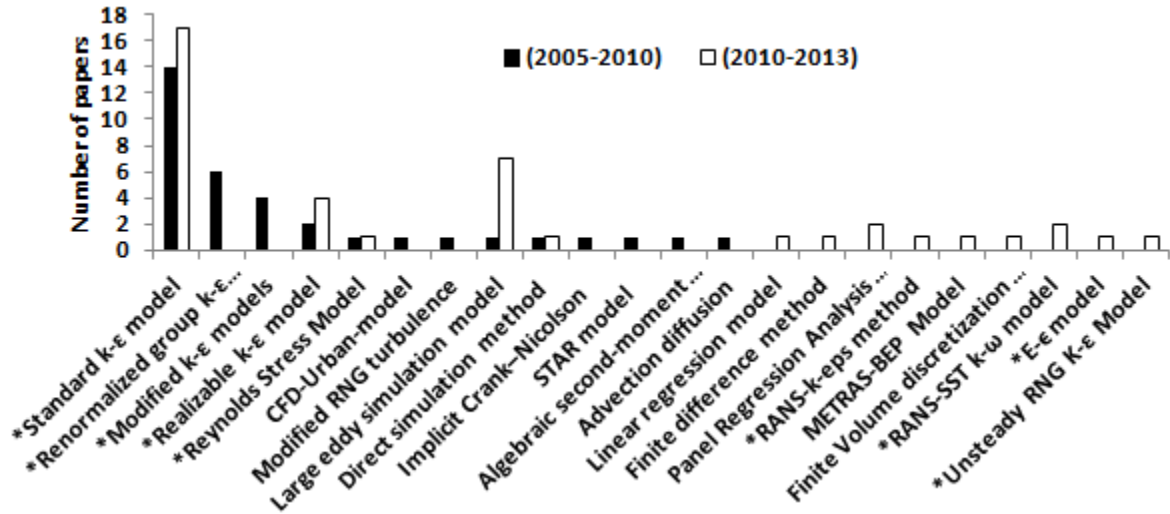


Figure 9. Implemented models (*denotes a RANS-based model)

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 of solver options, FLUENT is applicable to a wide range of engineering problems both laminar and turbulent, with various heat transfer modes, chemical reactions, and multi-phase flows. Notable, there is a growing trend to use ENVI-met. ENVI-met is 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 [97]. ENVI-met provides both spatial resolution (0.5-10m) and temporal variation (finest 10s 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].

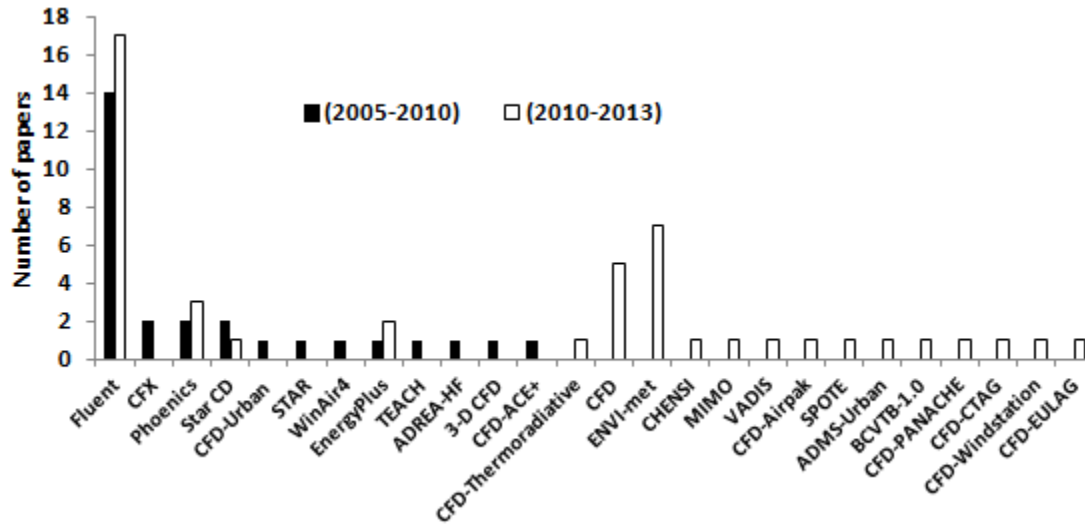


Figure 10. Selected software

New Developments

Two new developments were noted that may have a large impact on future modelling. The first was 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. CTAG is still computationally expensive compared to parameterized dispersion models [35].

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 [103-104].

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.

CONCLUSIONS

In a survey of nearly 100 micro-climate modelling papers over the past eight years four key trends were noted:

- The inclusion of fewer buildings (and often only one building), but with a much greater level of detail (especially vegetation and vehicle emissions). As part of this the study areas are now more often modelling actual (as opposed to hypothetical locations) and limited to the micro- and meso-levels, instead of a previous inclusion in the macro-scale
- A much greater usage of three-dimensional aspects (as opposed to two-dimensional ones) in both the domain and in the choice of elements.
- 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

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