COST 732 in practice: the MUST model evaluation exercise

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Abstract: The aim of this paper is to describe the use of a general methodology tailored to the evaluation of micro-scale meteorological models applied to flow and dispersion simulations in urban areas. This methodology, developed within COST 732, has been tested through a large modelling exercise involving many groups across Europe. The major test case used is the Mock Urban Setting Test (MUST) experiment representing an idealised urban area. It is emphasised that a full model evaluation is problem-dependent and requires several activities including a statistical validation that requires a careful choice of the metrics for the comparison with measurements.

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1   Introduction

COST Action 732 (2005–2009) was launched with the intent of improving and assuring the quality (fitness-for-purpose) of micro-scale meteorological models that are used for predicting flow and dispersion in urban or industrial environments. COST 732 started in July 2005 with a joint ESF/COST 732 Exploratory Workshop on Quality Assurance of Micro-Scale Meteorological Models held in Hamburg. The eventual impact of COST 732 is dependent upon whether the evaluation procedures suggested by the Action are widely accepted by the scientific community of model developers and model users. In May 2007 the first version of the evaluation procedure was released in order to provide a basis for discussions within the community. One of the main aims of COST 732 is that of establishing best practice methodologies and a standardisation of CFD modelling practise when used for meteorological applications within urban areas. The evaluation procedure proposed by COST 732 is presented in three documents that are publicly available on line at http://www.mi.uni-hamburg.de/Official-Documents.5849.0.html

- Background and Justification Document to support the Model Evaluation Guidance and Protocol, Version 1, May 2007 (Britter and Schatzmann, 2007a).

- Model Evaluation Guidance and Protocol Document, Version 1, May 2007 – a stand-alone document to assist the setting up and executing of a model evaluation exercise (Britter and Schatzmann, 2007b).

- Best Practice Guideline for the CFD simulation of flows in the urban environment, Version 1, May 2007 – based on published guidelines and recommendations, which mainly deal with prediction of the statistically steady mean flow and turbulence in urban areas under conditions of neutral density stratification (Franke et al., 2007).

The recommendations given in the documents listed above have been tested by COST 732 itself. The Mock Urban Setting Test (MUST), (Biltoft, 2001; Yee and Biltoft, 2004) which comprises field and wind tunnel experiments from flow and dispersion experiments carried out within and above a simulated urban setting made up from 120 standard size shipping containers, was selected for initial studies. The wind tunnel measurements within a scaled model (1 : 75) of that configuration were carried out at the University of Hamburg. (Bezpalcova, 2007). So far, several groups of numerical modellers (with most using CFD models) have simulated the wind tunnel MUST experiments following the model evaluation guideline. The experiments used were those with two main wind directions, 0° and –45° (and these correspond to 270° and 315°, respectively, in meteorological terminology) of the approaching flow. This study was launched in Athens in October 2006 and is the basis for COST 732 testing the evaluation procedures for urban flow and transport models. Attention is given to determining the quality (fitness-for-purpose) of the model.

2   Methodology

Several CFD models have been used by different groups from many European countries. They are: Miskam, Fluent, ADREA, Star-CD, Finflo, Cfx, Mitras, Tsu/M2UE, VADIS, Code_Saturne. Also non-CFD models, such as Lasat, ADMS-Urban, RAMS, OML, ESCAPE, CALPUFF, have received attention within COST 732. For comparison of numerical results with experimental data, both qualitative and quantitative approaches have been chosen. There is a common understanding that exploratory qualitative data analysis using graphical comparison between model and data and an intercomparison among models gives a simple, useful and transparent way of showing the strengths and weaknesses of models.

For the evaluation of a model both qualitative (through profiles and contours) and quantitative (through statistical analysis) approaches are needed, otherwise statistical parameters alone could obscure deficiencies of the model.

In our proposed methodology model results needs to be analysed in a combined way by means of

- contours of velocity components, Turbulent Kinetic Energy (TKE) and Reynolds stress components

- vertical and horizontal profiles of velocity components and TKE

- profiles of dimensionless concentration. In the example provided we only use the –45° approach flow case as concentration measurements were not available for the 0° case

- statistical analyses.

The first three are essentially a qualitative analysis while the fourth is quantitative. In our methodology, model results are quantitatively evaluated using direct point-by-point comparisons with wind tunnel data focusing on the mean velocity components, on the TKE, on the Reynolds stresses and on the pollutant concentrations. This approach was preferred over the alternative of using manipulated data such as estimating a maximum concentration on an arc and using it for model comparison purposes. To assess model

performance several statistical measures can be used, such as the Fractional Bias (FB), the Normalised Mean Square Error (NMSE), the fraction of predictions within a factor of two of observations (FAC2), the Geometric Mean (MG) bias and the geometric variance (VG). Typical magnitudes of the above performance measures and estimates of model acceptance criteria have been summarised by Chang and Hanna (2004) based on extensive experience with evaluating many models with many field data sets. The commonly accepted values for 'state of the art' model performance are: $-0.3 < FB < 0.3$; $NMSE < 4$; $FAC2 \geq 0.5$; $MG < 1$; $VG < 1.5$. Also the hit rate evaluation test (VDI, 2005) should be performed using a fractional deviation $D = 0.25$ and specific absolute deviations W for the different variables analysed (the hit rate must not fall below 66% for the comparison with wind tunnel data).

In this perspective, assuming that the set of models involved in COST 732 is a representative sample of the micro-scale models currently available and widely used, at least in a European context, with the MUST exercise the Action's intention is to suggest criteria for the 'state of the art' based on the model results. The state of the art is a dynamical concept; models constantly improve and the state of the art consequently changes. So the methodology which the Action is following will contain a procedure to update the criteria, so that if, in the future, new models are run using the COST 732-MUST case or other data, the value of the metrics reflecting the state of the art will be modified. Currently, such criteria are valid only for the COST 732-MUST dataset but future model comparisons with other datasets under COST 732 will provide more comprehensive model evaluation.

A somewhat different question concerns the 'fitness for purpose' criteria as these change with the intended purpose of the model. An important point to be addressed by a model user is whether the 'state of the art' will satisfy the 'fitness for purpose' criteria for the particular purpose of the modeller.

3   Results

Vertical and horizontal profiles of wind tunnel data and the results from the various model simulations have been collected in Excel spreadsheets that include a macro tool, which allows easy graphical comparisons. The tool was developed within this Action by Berkowicz et al. (2007). This tool was found to be extremely useful for exploratory data analysis to highlight both large errors and subtle differences among the models.

In this section we present, as an example of the qualitative evaluation, some profiles of the horizontal velocity component along the *x*-axis (U) and the vertical velocity component (W) for the 0° case (normalised with the reference wind velocity of undisturbed flow U_{ref}). We also show concentration profiles for the –45° approach flow case. Concentration values are expressed in a non-dimensional form as follows:

$$C* = \frac{CU_{ref}H^2}{Q} \tag{4}$$

where C is the calculated concentration, H the building height and Q the emission rate.

3.1 Wind profiles

For the 0° approach flow case, Figure 1 shows example vertical profiles at one measurement point in the spanwise street canyon at the middle of the array. From Figure 1, we note that the qualitative behaviour of the models is different. Some of them seem to underestimate U/U_{ref} in the layer occupied by the buildings, while others overestimate the velocity. Table 1 shows the validation metrics from two of the models involved. These metrics have been calculated considering all vertical profiles available. The agreement between models and experiments is good for the *U* velocity component with all metrics within the range or very close to the acceptance criteria limits. It should be noted that FB and NMSE parameters are without meaning for velocity components or variables which may assume both positive and negative values. Overall all models are not able to predict well the *W* component and they tend to underestimate it.

Figure 1   0° approach flow case: (a) sketch of the array showing the position (vertical line) of measurement profiles in the street canyon and (b) examples of modelled and measured vertical profiles of U/U_{ref} and W/U_{ref} (where mod indicates modelled results and *WT* indicates wind tunnel data)
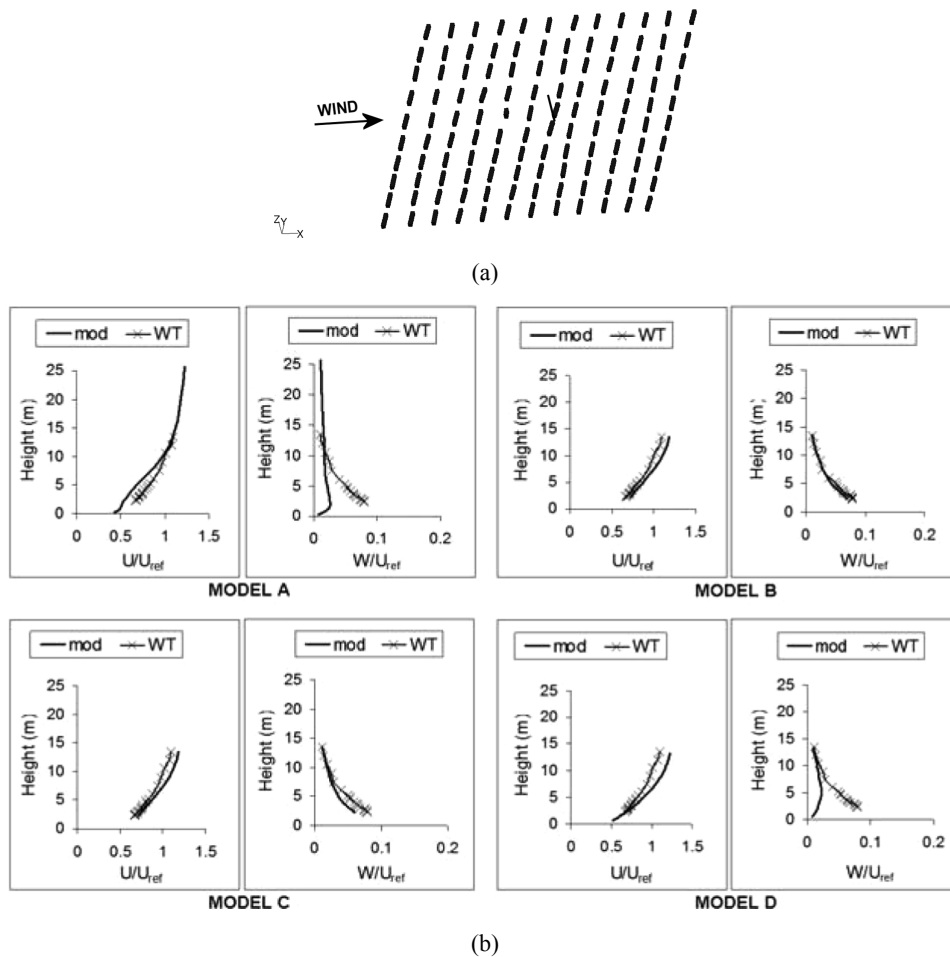

(a)

(b)

Table1   0° approach flow case: statistical quantities of U/U_{ref} and W/U_{ref} obtained from some models against wind tunnel data for all vertical profiles available

MODEL	FAC2 (U/U_{ref}; W/U_{ref})	Hit rate (U/U_{ref}; W/U_{ref})
B	0.88; 0.30	0.61; 0.24
C	0.92; 0.24	0.66; 0.17

3.2   Tracer concentration

The qualitative behaviour of the pollutant plume predicted by the models compares well with wind tunnel data. As an example Figure 2 shows concentration results in the middle of the array for the –45° approach flow case plotted at a constant height $z = 0.5$ H (where *H* is the height of the building).

Table 2 shows, as an example, the validation metrics for concentration from two of the models involved for all measurements points (256). The agreement is good for the two models with all metrics within or very close to the acceptance limits.

The Action has also collected results from the statistical analysis for all the models participating to the MUST exercise. Differences in the metrics for different models for the MUST data and for other datasets and the criteria for the 'state of the art' and for 'fitness for purpose' for typical purposes have been discussed. This has allowed to formulate a Best Practice Guideline for using the MUST case and to revise the Model Evaluation Guidance and Protocol Documents. Further detailed qualitative and quantitative results (Schatzmann et al., 2009) have been presented during several conferences and will be presented over the next years.

Figure 2   –45° approach flow case: (a) top view of the array, position of the source (black square in the upper part) and measurements points (left part). Wind blows from the top and (b) examples of modelled and measured C^* values along an horizontal profile perpendicular to the wind direction (black rhombi in Figure 2(a))
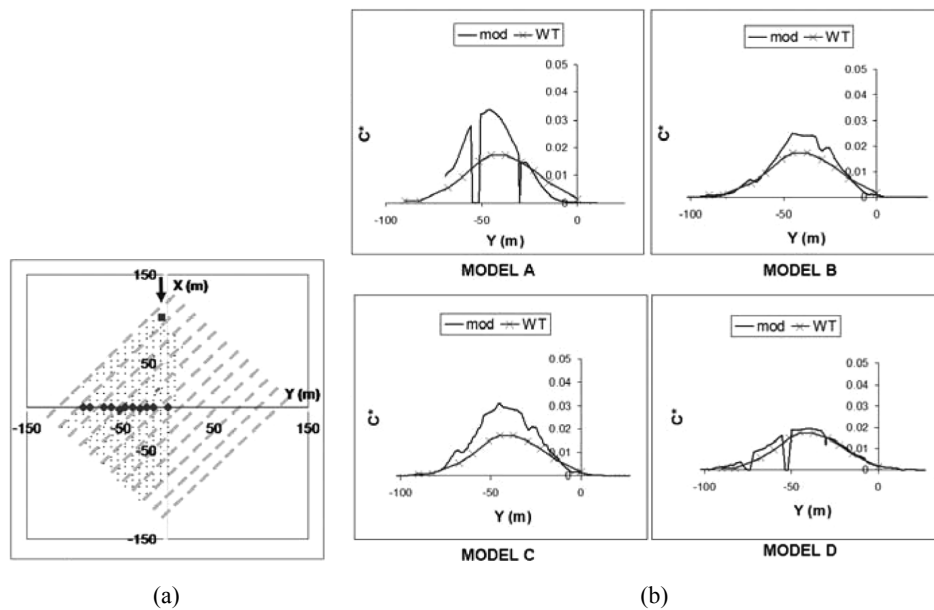

(a)   (b)

Table 2   −45° approach flow case: statistical quantities of dimensionless concentrations *C**
obtained from some models against wind tunnel data for all measurements points

MODEL	FB	FAC2	Hit rate
B	−0.26	0.97	0.68
C	−0.39	0.94	0.64

4   Lessons learnt and conclusions

The first qualitative comparison carried out in the COST 732 shows that flow and concentration model results compare relatively well with the measurements. The prediction for the *U* velocity component is better than for the *W* component. The Excel tool developed within the COST 732 has allowed us to make detailed studies of the differences in model results where the differences are not obscured by differences in presentation. Correct specification of the inlet profiles and specific aspects of two-equation turbulence models were thought to require further investigation.

The Action has finalised the MUST exercise and has suggested the best approach for further model evaluation for the standardisation of CFD modelling practise for micro-scale meteorological applications. This includes a critical review and refinement of the numerical results. This has been done by using outcome from some working groups which were formed during the Action to investigate specific aspects including boundary conditions, statistical measures and non-CFD model evaluations.

Acknowledgements

References

Berkowicz, R., Olesen, H. and Ketzel, M. (2007) http://www.dmu.dk/International/Air/Models/ Background/MUST.htm

Bezpalcova, K. (2007) *Physical Modelling of Flow and Diffusion in Urban Canopy*, PhD Thesis, Faculty of Mathematics and Physics, Charles University in Prague.

Biltoft, C.A. (2001) *Customer Report for Mock Urban Setting Test, DPG Document No. WDTCFR-01-121*, West Desert Test Center, US Army Dugway Proving Ground, Dugway, Utah, p.58.

Britter, R. and Schatzmann, M. (Eds.) (2007a) *Background and Justification Document to Support the Model Evaluation Guidance and Protocol Document*, COST Office Brussels, Belgium.

Britter, R. and Schatzmann, M. (Eds.) (2007b) *Model Evaluation Guidance and Protocol Document*, COST Office Brussels, Belgium.

Chang, J. and Hanna, S. (2004) 'Air quality model performance evaluation', *Meteorol. Atmos. Phys.*, Vol. 87, pp.167–196.

COST Action 732 (2005–2009) *Quality Assurance and Improvement of Micro-Scale Meteorological Models*, http://www.mi.uni-hamburg.de/Home.484.0.html

Franke, J., Hellsten, A., Schlünzen, K.H. and Carissimo, B. (Eds.) (2007) *Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment*, COST Office Brussels, Belgium.

Schatzmann, M., Olesen, H. and Franke, J. (Eds.) (2009) *COST 732 Model Evaluation Case Studies: Approach and Results*, COST Office, Brussels, Belgium.

VDI (2005) *VDI Guideline 3783 Part 9: 2005-11, Environmental Meteorology – Prognostic Micro-scale Wind Field Models – Evaluation for Flow Around Buildings and Obstacles*, Beuth Verlag, Berlin.

Yee, E. and Biltoft, C. (2004) 'Concentration fluctuation measurements in a plume dispersing through a regular array of obstacles', *Boundary Layer Meteorology*, Vol. 111, pp.363–415.