UNIVERSITY OF BIRMINGHAM

Coupling dynamics and chemistry in the air pollution modelling of street canyons: A review

Zhong, Jian; Cai, Xiaoming; Bloss, William

Link to publication on Research at Birmingham portal

Coupling dynamics and chemistry in the air pollution modelling of street canyons: a review

Jian Zhong, Xiao-Ming Cai* and William James Bloss

School of Geography, Earth & Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

Corresponding author. Tel.: (0121) 4145533; Fax: (0121) 4145528.

Email address: x.cai@bham.ac.uk (X.-M. Cai).

Abstract:

Air pollutants emitted from vehicles in street canyons may be reactive, undergoing mixing and chemical processing before escaping into the overlying atmosphere. The deterioration of air quality in street canyons occurs due to combined effects of proximate emission sources, dynamical processes (reduced dispersion) and chemical processes (evolution of reactive primary and formation of secondary pollutants). The coupling between dynamics and chemistry plays a major role in determining street canyon air quality, and numerical model approaches to represent this coupling are reviewed in this article. Dynamical processes can be represented by Computational Fluid Dynamics (CFD) techniques. The choice of CFD approach (mainly the Reynolds-Averaged Navier-Stokes (RANS) and Large-eddy Simulation (LES) models) depends on the computational cost, the accuracy required and hence the application. Simplified parameterisations of the overall integrated effect of dynamics in street canyons provide capability to handle relatively complex chemistry in practical applications. Chemical processes are represented by a chemical mechanism, which describes mathematically the chemical removal and formation of primary and secondary species. Coupling between these aspects needs to accommodate transport, dispersion and chemical reactions for reactive pollutants, especially fast chemical reactions with time scales comparable to or shorter than that of typical turbulent eddies inside the street canyon. Different approaches to dynamical and chemical coupling have varying strengths, costs and levels of accuracy, which must be considered

26   in their use for provision of reference information concerning urban canopy air pollution to

27   stakeholders considering traffic and urban planning policies.

28   **Capsule:**

29   Coupling between dynamics and chemistry plays a major role in determining street canyon air

30   quality. Different coupling approaches have varying strengths, costs and levels of accuracy.

31   **Keywords:** Air pollution; Street canyon; Computational Fluid Dynamics (CFD); Large-eddy

32   simulation; Box model; Chemical mechanism.

33

34

35

36

37

38

39

40

41

42

43

44

45

1 Introduction

The terminology "street canyon" typically describes a restricted space in an urban area with surrounding buildings, usually along both sides of a street (Jeong and Andrews, 2002). In such an atmospheric compartment, natural air ventilation through dynamical processes is drastically constrained compared with open space (Cheng et al., 2008). Emissions from vehicles, such as nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs) and particulate matter (PM), are predominant among various anthropogenic pollutant sources inside street canyons in urbanised areas. Many such emitted species are reactive (Park et al., 2015), undergoing chemical processing within the street canyon to generate secondary pollutants such as ozone (O_3) and secondary aerosol. The deterioration of air quality in street canyons therefore occurs due to combined effects of the emissions source, dynamical processes (reduced dispersion) and chemical processes (evolution of reactive primary and secondary pollutants) (Li et al., 2008b). The urban canopy is the location in which the majority of outdoor activities of the urban population occurs, and hence where substantial human exposure results for pedestrians, road-users and occupants of adjacent buildings which may gain their ventilation from the outdoor (canyon) environment. Exposure to such environments causes adverse health effects (Solazzo et al., 2011). Since both the primary and secondary pollutants exhibit inhomogeneous distributions in urban street canyons and vary substantially in abundance with time, it is not an easy task to assess individual or population exposure to such air pollutants. The pedestrian level (breathing height) in street canyons is expected to experience particularly high levels of pollutants due to the proximity to vehicle emissions. Pollutant abundance within street canyons frequently far exceeds that in the wider urban background; in 2005, for example, measured data at the London Marylebone Road 'super-site' showed that NO_2 hourly concentrations exceeded the hourly objective for 853 times compared with 0 times at the nearby London Westminster urban background site (Bady et al.). Both short term exposure to high levels of pollutants and long term exposure to lower levels may cause adverse health impacts (WHO, 2000). Air quality objectives, specified for long term averages (hours, days

72 or annual) may be inadequate to account for the exposure associated with the real nonlinear

73 fluctuations in pollutant abundance in urban street canyons, with repeated aperiodic peaks present

74 for short periods. Understanding both dynamic and chemical processes governing the abundance of

75 reactive pollutants in street canyons is of vital importance to accurately quantify personal exposure,

76 and to help urban planners develop policies (e.g. street canyon design and utility of green

77 infrastructure) to mitigate such health impacts.

78 Various approaches have been undertaken to investigate air pollution in street canyons, such as field

79 measurements, physical modelling, numerical modelling and parametric (operational) modelling.

80 Field measurements can provide first-hand information on pollutant abundance (subject to the

81 limitations of measurement technologies), air flow and pollutant dispersion, and can ground-truth

82 models, but with some limitations (e.g. challenges to data interpretation, uncontrollable

83 meteorological conditions, low spatial coverage, and typically high expense). Physical modelling

84 (e.g. wind tunnels and water channels) only provides insight into dynamics; such approaches are

85 able to fully control testing parameters and sampling points, and to provide well-documented

86 datasets for the evaluation of numerical models. Due to scale limitations, it is a challenge for such

87 models to replicate fully the large-scale atmospheric turbulence of the real world and hence to scale

88 the nonlinear photochemical reactions with a wide range of time scales. Numerical modelling can

89 provide high spatial and temporal distributions of flow and pollutant fields in street canyons, with

90 increasing accuracy and precision compared with the available observations for validation. Such

91 models can be repeated with controllable test parameters at relatively low economic expense.

92 However, they normally require a high level of computational resource and may require substantial

93 input information (computational domain, flow characteristics, chemical schemes). Parametric

94 modelling can provide useful time-series information regarding pollutant abundance for regulatory

95 applications, based on semi-empirical parameterisation of street canyons (and emissions). This

96 approach is relatively simple to use and demands far less computational cost than numerical

97   modelling. However, due to the inherent semi-empirical assumptions, parametric models are unable

98   to reproduce the detailed distribution of the flow or pollutant fields in street canyons.

99   Recent reviews have provided an overview of specific individual aspects of urban street canyon

100   dynamics or pollution or chemistry. Ahmad et al. (2005) reviewed wind tunnel experiments on wind

101   flow and pollutant dispersion patterns in street canyons. Vardoulakis et al. (2003) examined a range

102   of approaches (from measurements to modelling) for the study of air quality in street canyons,

103   focussing upon measurements and parametric modelling approaches, with little discussion of

104   computational fluid dynamics (CFD) modelling. Subsequently, Li et al. (2006) conducted a separate

105   review on the CFD modelling of wind flow and pollutant transport in street canyons, focussing

106   upon dynamical processes of pollutant dispersion within street canyons, rather than on the chemical

107   processes. Yazid et al. (2014) reviewed a variety of studies (from measurements to modelling)

108   addressing flow structure and pollutant dispersion to provide guidelines for urban planning

109   strategies. While this study briefly considered chemical reactions, there is limited discussion on the

110   coupling of dynamics and chemistry. With ongoing improvements of advanced computer

111   technology, it has become feasible to apply detailed numerical modelling approaches to explore the

112   coupling between dynamical and chemical processes involving pollutant dispersion and

113   transformation in street canyons. The dynamics-chemistry coupling approach has increasingly been

114   applied to the street-canyon scale (e.g. Kwak and Baik (2014) and Zhong et al. (2015)) , with a

115   range of related, but distinct approaches, and associated advances in our understanding of urban

116   street canyon pollutant abundance. It is in this new context that the present paper reviews progress

117   in the development of coupling between dynamics and chemistry, as applied to street-canyon air

118   pollution modelling, with a focus upon gas-phase processes.

2 Modelling dynamics in street canyons

119

120   Street canyon geometry is normally characterised by the aspect ratio, i.e. H/W (building-height-to-

121   street-width, herein referred as to AR) and L/W (building-length-to-street-width). According to

122   Vardoulakis et al. (2003), street canyons might be classified into avenue $(AR \leq 0.5)$, regular

123   $(0.5 < AR < 2)$ and deep $(AR \geq 2)$ street canyons or into short $(L/W \leq 3)$, medium

124   $(3 < L/W < 7)$ and long street canyons $(L/W \geq 7)$. This classification is based on the geometrical

125   detail of a street canyon, which may be empirically derived and widely used. When L is infinitely

126   large, this corresponds to a two-dimensional (2D) street canyon; otherwise, a three-dimensional (3D)

127   street canyon architecture must be considered and the value of L describes the distance between two

128   street intersections. Flow patterns in street canyons under neutral meteorological conditions with

129   perpendicular approaching wind can be classified into three main regimes (Oke, 1987): isolated

130   roughness flow (IRF), wake interference flow (WIF) and skimming flow (SF). The IRF regime is

131   related to widely spaced buildings ($AR < 0.3$). The WIF regime is associated with the closer spaced

132   buildings ($0.3 < AR < 0.7$). The SF regime occurs in more tightly spaced buildings ($AR > 0.7$),

133   representing the worst-case scenario for pollutant dispersion.

134   **2.1 Numerical modelling**

135   As a numerical modelling technique, CFD is a powerful tool to explore experimental flow problems,

136   to characterise air pollutant transport and dispersion processes, and to provide a detailed distribution

137   of canyon flow and pollutant dispersion with high spatial-temporal resolution (Chang, 2006). A

138   CFD package may include a series of numerical governing equations for turbulent flow and

139   pollutant dispersion, potentially involving the coupling of both dynamics and chemistry. The

140   turbulence closure schemes for the CFD packages are classified into two categories: Reynolds-

141   averaged Navier–Stokes (RANS) and Large-Eddy Simulation (LES). RANS resolves only the mean

142   time-averaged properties with all the turbulence motions to be modelled. In place of the time-

143   averaging used in RANS, LES adopts a spatial filtering operation and consequently resolves large-

144   scale eddies directly and parameterises small-scale eddies using sub-grid scale (SGS) turbulence

145   models. In this aspect, the RANS approach is easier to be established and computationally faster

146   than LES. The atmospheric turbulent flow in and above street canyons involves turbulent eddies on

147   a variety of scales (McNabola et al., 2009). The sizes of large-scale eddies are usually comparable

148   to the characteristic length of atmospheric turbulent flow, and are dependent on the street canyon

149   geometry and turbulent flow boundary conditions. Small-scale eddies typically have a universal

150   behaviour throughout the computational domain and are more dependent on the local energy

151   dissipation. Applications of RANS and LES in street-canyon dynamics are discussed below.

152   **2.1.1 Reynolds-averaged Navier–Stokes (RANS)**

153   RANS can determine the mean turbulent flow in a domain quickly and has been widely used in

154   engineering applications. The most commonly used RANS turbulence models for the investigation

155   of the urban canopy flow include the standard $k - \varepsilon$ (k is the turbulence kinetic energy and ε is the

156   dissipation rate) model, the renormalised-group (RNG) $k - \varepsilon$ model, the realizable $k - \varepsilon$ model and

157   the Reynolds Stress model (RSM). The $k - \varepsilon$ models are generally eddy-viscosity models and they

158   solve k and ε from their respective transport equations. The turbulence viscosity (μ_t) is calculated

159   from $\mu_t = \rho C_\mu \dfrac{k^2}{\varepsilon}$ (where C_μ is a modelling constant, ρ is the density), which are then used to

160   parameterise the Reynolds stresses in the $k - \varepsilon$ models. However, in the RSM, it calculates

161   Reynolds stresses explicitly based on their respective transport equations.

162   The standard $k - \varepsilon$ model is well documented and can perform well in reproducing general

163   structure for fully turbulent flow (Tsai and Chen, 2004). However, for street-canyon flow, it does

164   not predict turbulence kinetic energy with good accuracy in regions close to the walls or to the shear

165   layer at the canyon roof level (Sini et al. (1996); Hassan and Crowther (1998); Baik and Kim

166   (1999)). Smagorinsky (1963) evaluated the standard $k - \varepsilon$ model using a water channel experiment

167   (Baik et al., 2000) and investigated the effect of inflow turbulence intensities (Kim and Baik, 2003)

168   on the flow dispersion in the street canyon. The turbulence kinetic energy and diffusivity were

169   found to increase with an increase in the inflow turbulence intensity. Solazzo et al. (2008) employed

170   the standard $k - \varepsilon$ model to investigate the effect of traffic-induced turbulence. Compared to a wind

171   tunnel experiment (Kastner-Klein et al., 2001), the model performed well in terms of predicting the

172   turbulence kinetic energy and mean horizontal velocity, but showed limitations in reproducing the

173   mean vertical velocity.

174   The RNG $k-\varepsilon$ model applies a rigorous statistical technique (i.e. the renormalisation group

175   mathematical theory (Yakhot and Orszag, 1986)) to determine the effective turbulent viscosity and

176   includes an additional source term in the ε equation to capture the interaction between turbulence

177   dissipation and mean shear. This model has been successfully implemented in simulating the street

178   canyon transitional flow. Memon et al. (2010) applied the RNG $k-\varepsilon$ model to 2D isolated street

179   canyons considering heating situations. Compared with a wind tunnel experiment (Uehara et al.,

180   2000), there was a good agreement for the normalised potential temperature. The model

181   underestimated the normalised horizontal velocity at the canyon roof level (by 10%) because the

182   effect of 3D city blocks and roughness elements in the experiment not being fully represented by

183   the 2D model. Kim and Baik (2004) carried out a 3D CFD model simulation coupled with the RNG

184    $k-\varepsilon$ model to examine the wind flow in street canyons. Although their model reproduced the flow

185   separation by buildings and reversed flow, it underestimated the turbulence kinetic energy and wind

186   velocity compared with a wind tunnel experiment (Brown et al., 2000). Chan et al. (2002)

187   conducted a series of $k-\varepsilon$ model simulations to study the flow dispersion in a 2D isolated street

188   canyon. Compared to wind tunnel experiments, the RNG $k-\varepsilon$ approach was found to be optimal.

189   They attributed this to the analytically derived formula of turbulent viscosity in the RNG

190    $k-\varepsilon$ model.

191   The realizable $k-\varepsilon$ model has an improved equation for ε considering vorticity fluctuation and

192   uses a variable of C_{μ} (while a constant value is adopted in both the standard $k-\varepsilon$ model and the

193   RNG $k-\varepsilon$ model) to derive the turbulence viscosity. This model provides better performance for

194   flows involving separation, rotation, and recirculation. Tian et al. (2009) developed an idealised 3D

195   model based on the realizable $k-\varepsilon$ model to investigate the flow dispersion around arrays of

196   buildings. Their model reproduced the secondary oval vortices around the buildings and the air

197 exchange between the inside and outside street canyons. Gromke and Blocken (2015) adopted the

198 realizable $k - \varepsilon$ model to simulate the flow and dispersion in and above 3D street canyons with

199 avenue-trees. Their study demonstrated the capability of the realizable $k - \varepsilon$ model to simulate the

200 flow and turbulence involving trees.

201 The RSM explicitly calculates the individual Reynolds stresses (poorly represented by the

202 $k - \varepsilon$ models). Thus in theory the RSM can perform better for complex flows (e.g. street canyon

203 flow) than the $k - \varepsilon$ models. However, the RSM is more complex involving more terms with more

204 uncertainties to be modelled and greater computational cost. Nazridoust and Ahmadi (2006) applied

205 the RSM, the standard and RNG $k - \varepsilon$ models to study the airflow and pollutant dispersion in 2D

206 street canyons. The RSM generally agreed better with wind tunnel experimental data for pollutant

207 concentrations among the turbulence models used in their study. The standard $k - \varepsilon$ model and the

208 RNG $k - \varepsilon$ model predicted similar results for pollutant concentrations, in alignment with the

209 findings of Chang and Meroney (2001). Koutsourakis et al. (2012) evaluated the performance of the

210 RSM, standard $k - \varepsilon$ model and RNG $k - \varepsilon$ model in simulating the street canyon flows using six

211 experimental datasets (i.e. Baik et al. (2000), Hoydysh and Dabberdt (1988), Depaul and Sheih

212 (1986), Kovar-Panskus et al. (2002), Sahm et al. (2002) and Li et al. (2008a). The model with the

213 best performance could be any of the three turbulence models depending on the experimental

214 dataset used (e.g. vertical and horizontal velocities, and pollutant concentrations). The RNG $k - \varepsilon$

215 model generally possesses the best performance and has an improvement compared with the

216 standard $k - \varepsilon$ model. Although the RSM can reproduce better near-wall phenomena than $k - \varepsilon$

217 models, the RSM needs much more computational time and has more difficulty to achieve

218 convergence. Due to high uncertainties in street canyon geometry and wind conditions for both

219 models and experiments, consideration of only one experimental dataset was found to be

220 insufficient when assessing the performance of a particular turbulent model.

2.1.2 Large-Eddy Simulation (LES)

Although RANS is computationally fast and extensively adopted, it suffers some limitations such as handling complex geometries involving separation (such as building blocks), near-wall treatment and the empirical model parameters. The LES approach performs better than RANS in terms of modelling accuracy for flow turbulence, but has greater computational cost. With recent advances in computer technology, LES is increasingly affordable as a promising tool to investigate turbulent mixing processes for research purposes. Salim et al. (2011a) claimed that LES could potentially serve as an alternative to experiment for prediction of street-canyon flow characteristics in urban planning. The most commonly used SGS turbulence models in the LES approach to investigate the urban canopy flow include the Smagorinsky SGS model, the dynamic Smagorinsky SGS model and the one-equation SGS model.

The Smagorinsky SGS model (Smagorinsky, 1963) is widely used because of its simplicity and numerical stability in the parameterisation of the SGS stresses assuming that the small scale energy production and dissipation are in equilibrium. This SGS model can simulate many flows with reasonable accuracy. Cui et al. (2004) developed an LES model (the Smagorinsky SGS model), based on the Regional Atmospheric Modelling System (RAMS) meteorological code, to investigate turbulent flow in and above a street canyon (AR=1). Their study provided a detailed analysis of the turbulent canyon flow structure as well as the contributions of ejection or sweep events near the roof level to the momentum flux between the canyon and the boundary layer aloft. In comparison with wind-tunnel experimental data, their results showed that the LES model underestimated the momentum flux, indicated by a weaker mean primary vortex inside the canyon than that measured. They attributed this to (i) the limited domain size (which may underestimate the turbulent intensity above the canyon) and (ii) the relatively coarse mesh size near roof level where a strong wind shear and associated instability were present. Cai et al. (2008) further adopted this LES model (the Smagorinsky SGS model) based on RAMS meteorological code (Cui et al., 2004) to simulate the transfer characteristics of passive scalars corresponding to area sources over the road surface, the

247   upstream wall and the downstream wall, respectively, in a 2D street canyon. By comparing with

248   wind-tunnel experimental data (i.e. Meroney et al. (1996) and Kastner-Klein and Plate (1999)), they

249   demonstrated the LES model captured the main characteristics of canyon flow and scalar dispersion.

250   The dynamic Smagorinsky SGS model (Germano et al., 1991) adopts the dynamical procedure to

251   diagnose a local value for the Smagorinsky constant (which is used as a constant value in the

252   Smagorinsky SGS model) based on the information from resolved scales. This dynamic model

253   performs better in terms of the flow in the vicinity of boundaries compared with the traditional and

254   simple Smagorinsky SGS model. However, the dynamic procedure requires much more

255   computational cost and may lead to numerical instability. Michioka et al. (2011) adopted an LES

256   model (the dynamic Smagorinsky SGS model) to examine the flow and pollutant dispersion

257   mechanism in a 2D street canyon (AR=1). Compared with wind-tunnel experiments, the LES model

258   provided qualitatively correct predictions of the velocity statistics, with small discrepancies when

259   the computational domain size was smaller. They also found that the accuracy of the LES model

260   would be improved with an increase of the streamwise domain size, i.e. to more than 10 times the

261   canyon height, as suggested by Kanda et al. (2004). Michioka and Sato (2012) investigated the

262   effect of incoming turbulent structure on the pollutant removal from 2D idealised street canyons

263   using the same LES model as that adopted by Michioka et al. (2011). Their study showed that the

264   turbulence structure of external flow influenced significantly on the turbulence kinetic energy

265   within the canyon and the momentum exchange at the canyon roof level, but less on the mean

266   velocity within the canyon. Liu et al. (2005) employed an LES model (the dynamic Smagorinsky

267   SGS model) to investigate air exchange rate (ACH) and pollutant exchange rate (PCH) in street

268   canyons with different aspect ratios of 0.5, 1.0 and 2.0 based on the detailed LES database by Liu

269   and Barth (2002) and Liu et al. (2004). The ACH (PCH) was the integration of the product of

270   instantaneous fluctuating vertical velocity (and the instantaneous pollutant concentration) over the

271   air exchange area at the canyon roof level. The transient turbulence properties at the roof level were

272   well represented by the ACH and PCH. It was found that more pollutants were trapped inside the

273   street canyon near the ground with an increase in canyon aspect ratio.

274   The one-equation SGS model (Schumann, 1975) solves an additional transport equation for the

275   SGS turbulence kinetic energy conservation to account for the SGS motion. This model keeps track

276   of the total energy in the SGS, which are not included by the Smagorinsky models. Cheng and Liu

277   (2011) developed an LES model (the one-equation SGS model) to investigate the turbulent flow and

278   pollutant removal in and above 2D street canyons (AR=1). In comparison with the model

279   configuration of Cui et al. (2004) , their grid resolution was slightly coarser (by 30 %) in the

280   streamwise direction, but their domain sizes were larger by factors of 3, 1.5 and 2.7 in the

281   streamwise, spanwise and vertical directions, respectively. However, the simulated intensity of the

282   mean primary vortex in the canyon was weaker than that of Cui et al. (2004), and they therefore

283   concluded that increasing LES domain size cannot fully rectify the under-predicted intensity of

284   mean primary vortex. This comparison indicated that well-resolved shear layers at the canyon roof

285   level with high gradients of velocities may be required and worth thorough investigation, e.g. a

286   stochastic backscatter model to increase the momentum transfer across the canyon roof level

287   (O'Neill et al., 2015). Li et al. (2008b) and Li et al. (2009) adopted LES models (based on the one-

288   equation SGS model) to handle the flow and pollutant dispersion for deep street canyons with high

289   ARs up to 10. The multiple primary vortices inside those deep street canyons were well reproduced

290   by their model.

291   **2.1.3 Comparison of RANS and LES**

292   Walton et al. (2002) and Walton and Cheng (2002) compared LES (the dynamic Smagorinsky SGS

293   model) and RANS (the standard $k - \varepsilon$ model) with field measurements and found that the LES

294   model provided the better agreement with measurements, possibly due to the more accurate

295   prediction of the turbulent intensities of the flow. Cheng et al. (2003) showed that both LES (the

296   dynamic Smagorinsky SGS model) and RANS (the standard $k - \varepsilon$ model) could predict the main

297   features of the *mean* air flow over an array of urban buildings with reasonable accuracy although

298   LES performed better than RANS in terms of capturing the details of the flow within the urban

299   canopy. They reported that the computational cost of LES was about 100 times that of RANS. Xie

300   and Castro (2006) also found that although LES (the Smagorinsky SGS model) better captured

301   turbulent flow around buildings than RANS (the $k - \varepsilon$ models and RSM), its computational cost

302   was at least an order of magnitude greater than that of RANS. Santiago et al. (2010) and Dejoan et

303   al. (2010) reported that the local mean flow quantities predicted by LES (the Smagorinsky SGS

304   model) were closer to the Mock Urban Setting Test (MUST) data than that predicted by RANS (the

305   standard $k - \varepsilon$ model). Tominaga and Stathopoulos (2011) applied both LES (the Smagorinsky

306   SGS model) and RANS (the RNG $k - \varepsilon$ model) to simulation of flow dispersion in a street canyon

307   (AR=1). LES was found to give better results than RANS compared with a wind tunnel experiment.

308   The turbulence diffusion was well reproduced by LES, but underestimated by RANS. The

309   performance in modelling turbulence diffusion by LES or RANS played an important role in the

310   accuracy of pollutant dispersion predictions (Tominaga and Stathopoulos, 2010). Salim et al.

311   (2011a) and Salim et al. (2011b) evaluated the performance of LES (the dynamic Smagorinsky SGS

312   model) and RANS (the standard $k - \varepsilon$ model and RSM) for the prediction of flow dispersion in a

313   street canyon (AR=1) with avenue-like trees. It was found that LES predicted significantly more

314   accurate better flow dispersion than RANS. Compared to RANS, LES provided better

315   representation of scenarios with trees since LES can capture intermittent and unsteady flow

316   fluctuations. Chung and Liu (2013) compared LES (the one-equation SGS model) and RANS (the

317   RNG $k - \varepsilon$ model adopted in Liu et al. (2011)) in the calculation of ACH and PCH. They found

318   that the contributions of the turbulent components to ACH and PCH are much more in the LES than

319   those in the RANS, highlighting the importance of turbulence in the transport and dispersion of

320   flow and pollutants.

321   **2.2 Simplified parameterisation**

322   Although numerical modelling is able to capture temporally and spatially detailed information

323   about dynamics in street canyons, it is still very complex and computationally expensive for many

324   practical applications. Parametric modelling based on simple operational relationships between the

325   street-canyon flow and dispersion conditions is an alternative tool, which is relatively simple and

326   demands much less computational cost (Murena et al., 2009). Numerical modelling, in turn, can

327   serve to better evaluate and provide algorithms for implementation within parametric modelling.

328   Detailed applications of the parametric modelling are given in the review papers of Vardoulakis et

329   al. (2007) and Kakosimos et al. (2010). Here, we focus on simplified parameterizations of dynamics

330   in street canyons.

331   Turbulent exchange (transfer) between the street canyon and the overlying atmospheric boundary

332   layer controls pollutant abundance in the street canyon (Barlow et al., 2004) and plays a uniquely

333   important role in parametric modelling (Murena, 2012). This turbulent exchange can be represented

334   by a simplified parameter called the 'transfer velocity' (Salizzoni et al., 2009) or 'air ventilation

335   rate' (Liu and Leung, 2008), herein referred to as 'exchange velocity' (Bright et al., 2013), which

336   may be defined in a bulk format through Fick's law of diffusion: $F_c = w_e (C_{can} - C_B)$, where F_c is

337   the pollutant flux per unit area at the roof level, w_e is the exchange velocity, and C_{can} and C_B are

338   the pollutant concentrations inside the canyon and at the background boundary layer, respectively.

339   A parameterisation of the exchange velocity can be derived from a more comprehensive model (e.g.

340   RANS or LES) of a specific street-canyon flow (if considering the street canyon as a box), e.g. Liu

341   et al. (2005); Bright et al. (2013). More practically in the STREET model (Johnson et al., 1973) and

342   the Operational Street Pollution Model (OSPM) (Buckland, 1998), it is assumed that the exchange

343   velocity is proportional to the characteristic velocity in the overlying boundary layer. However, the

344   dependence of exchange velocity on the street-canyon flow can be very complex and influenced by

345   many parameters. Murena et al. (2011) investigated the effects of the external wind speed on the

346   exchange velocity and a nearly linear relationship between them was found. Salizzoni et al. (2011)

347   found that the turbulent exchange was dependent on the coupling between the turbulence in the

348   shear layer and turbulent eddies in the external atmospheric flow. Caton et al. (2003) showed that

349   under lower external turbulence, the shear layer turbulence governed the exchange processes and a

350 linear assumption between the exchange velocity and the external wind speed could be derived, but

351 under higher external turbulence, the exchange processes were dominated by the external

352 turbulence and depended upon both the turbulent structure of the incoming flow and that of the

353 shear layer. Liu et al. (2011) and Solazzo and Britter (2007) investigated the effect of aspect ratio

354 on the exchange velocity and also found a linear relationship for a given AR, but also a varying

355 relationship between the exchange velocity and the external wind speed depending on the flow

356 regimes involved.

357 Such simplified parameterisations of turbulent exchange between the street canyon and the

358 overlying atmospheric boundary layer represents the overall integrated effect of the dynamics in

359 street canyons, but necessarily fails to reproduce the flow field within street canyons. The

360 introduction of 'exchange velocity' enables the application of parametric models (such as the box

361 model approach) into street canyon modelling. A street canyon is considered as a single well-mixed

362 (homogeneous) box, assuming that emissions into the box are mixed instantaneously and uniformly

363 distributed. This simplified dynamical framework permits relatively complex chemistry to be

364 afforded within street canyon modelling.

3 Chemistry for air pollution modelling

366 Modelling dynamics in street canyons, which determines the evolution and physical removal of

367 atmospheric pollutants, is only one component of the coupling approach of dynamics and chemistry.

368 The representation of atmospheric chemistry for air pollution modelling also plays an important role

369 for reactive species. Considering the street-canyon scale (short distance from emissions sources to

370 receptors), the time scale of pollutant transport is of the order of minutes and therefore chemical

371 transformation processes of significance in street canyons are those which display comparable (or

372 shorter) timescales. Thus, some pollutants (such as CO and many hydrocarbons), which are not

373 significantly influenced by chemical transformation on the second-to-minute timescales, can be

374 regarded as passive scalars (non-reactive species) in a street canyon context. However, this is not

375   the case for short-lived pollutants (such as NO_2 and O_3) and highly reactive chemical species (such

376   as hydroxyl radical (OH), hydroperoxy radical (HO_2) and organic peroxy radicals (RO_2)). For such

377   species, chemical reactions must be taken into account for the prediction of pollutant abundance in

378   street canyons. A chemical mechanism describes mathematically the chemical processes in the

379   atmosphere for the removal and formation of primary and secondary chemical species (Jimenez et

380   al., 2003), as discussed below, with a focus upon gas-phase processes.

381   **3.1 Simple NO_x-O_3 chemistry**

382   The simple NO_x-O_3 chemistry (Smagorinsky, 1963) describes the photochemical reactions between

383   NO, NO_2 and O_3. In the presence of sun light, NO_2 is rapidly photolysed leading to NO and O_3

384   formation ($NO_2 + hv \rightarrow NO + O$; $O + O_2 + M \rightarrow O_3 + M$; hv represents a solar photon; M denotes

385   a third body molecule which absorbs excess energy so that O and O_2 may recombine to form O_3)

386   and NO can also react quickly with O_3 to re-form NO_2 ($O_3 + NO \rightarrow NO_2 + O_2$). NO_x emitted from

387   vehicles into the street canyon is predominantly in form of NO with a small (but in many

388   environments increasing) fraction of NO_2. Within the urban environments, the NO_x-O_3 titration

389   interaction with freshly emitted NO can result in a significant local sink for O_3 in street canyons,

390   providing a reduction of O_3 level compared with the surrounding rural areas (or overlying canopy

391   layer). On a city-wide basis, this effect is also called the "urban decrement" (Munir et al., 2013).

392   Due to its simplicity, the simple daytime NO_x-O_3 system has been previously adopted in parametric

393   modelling, e.g. OSPM (Berkowicz, 2000) and ADMS (McHugh et al., 1997). The incorporation of

394   such simple chemistry into street canyon dynamics model can also be affordable especially for

395   otherwise expensive LES approaches (e.g. Baker et al. (2004)).

396   **3.2 Complex chemistry**

397   The simple NO_x-O_3 chemistry only accounts for daytime NO_x-O_3 interactions, without

398   consideration of other NO_y (reactive nitrogen oxides) species, nighttime processing, and the

399   oxidation of VOCs. Therefore, more realistic chemistry involving detailed inorganic and VOCs

400   reactions should be also considered for a comprehensive description of the urban atmosphere. Such

401   representations may include the reactions of radical species (e.g. OH, HO_2 and RO_2) which may

402   result in additional (non-O_3) conversion of NO to NO_2, and hence to net ozone / oxidant production,

403   that cannot be captured by the simple NO_x-O_3 chemistry. There are a wide range of mechanisms

404   (from near-explicit to substantially reduced mechanisms) with varying complexity considering both

405   NO_x and VOCs chemistry which have been applied in street canyon studies, and which are briefly

406   discussed below.

407   **3.2.1 MCM**

408   The Master Chemical Mechanism (MCM) is a near-explicit chemical mechanism, representing in

409   detail the gas-phase tropospheric degradation of primary VOCs and formation of (gaseous)

410   secondary pollutants (Jenkin et al., 1997). The MCM v1.0 consists of over 2,400 species and 7,100

411   reactions describing the degradation of 120 VOCs (Derwent et al., 1998). The MCM v2.0 updates

412   the chemistry of aromatic hydrocarbons and includes 3,487 species and 10,763 reactions

413   (Whitehouse et al., 2004). To improve the chemical degradation of aromatics (Jenkin et al., 2003),

414   the MCM v3.0 was developed, containing 12,691 organic reactions for 4,351 organic species, and

415   46 inorganic reactions (Saunders et al., 2003). To promote the understanding of aromatic photo-

416   oxidation (Bloss et al., 2005), MCM v3.0 was updated to MCM v3.1 (about 13,500 chemical

417   reactions and 5,900 species (Pinho et al., 2007)) and MCM v3.2 (about 17,000 chemical reactions

418   and 6,700 species (Jenkin et al., 2012)). The MCM has been evaluated against an extensive

419   experimental database from photochemical reaction chambers and field campaigns. Due to its near-

420   explicit nature, the MCM is principally employed within box models, and is usually considered too

421   expensive for 3D grid-based air pollution models. For such applications, it is necessary to develop

422   reduced chemical mechanisms which of an appropriate size, and yet which retain a quantitative

423   description of the atmospheric chemistry. The MCM may also be considered as a reference or

424   benchmark mechanism for developing and evaluating such reduced chemical mechanisms. Reduced

425   techniques include lumping, sensitivity analysis and timescale analysis approaches (Neophytou et

426 al., 2004). The lumping technique condenses several unique species into single ones (Makar and

427 Polavarapu, 1997) and has been the most frequently employed approach to the reduction of

428 chemical mechanisms. Three approaches are commonly used (Zaveri and Peters, 1999), i.e.

429 surrogate species, lumped molecule (lumping VOCs into a series of categories according to

430 similarity of oxidation reactivity) and lumped structure (lumping VOCs according to their chemical

431 nature as reflected in their molecular structures). The sensitivity analysis technique, also called

432 "iterative screening and structure analysis", uses chemical reaction and sensitivity analysis to

433 identify sensitive or key species by calculating concentrations of some species as a function of

434 others (Mauersberger, 2005). Timescale analysis removes fast-reacting "steady-state" species,

435 replacing these with calculated values, by distinguishing between "fast" and "slow" chemical time

436 scales using the quasi-steady-state approximation (Lovas et al., 2006).

437 **3.2.2 CRI Mechanism**

438 The Common Representative Intermediates (CRI) Mechanism is a reduced chemical mechanism

439 with intermediate complexity. The CRI is derived from the reference benchmark mechanism (MCM

440 v3.1) using a lumped structure technique (Jenkin et al., 2008) based on the assumption that the

441 number of reactive bonds (i.e. C-C and C-H) represent the index of the photochemical ozone

442 production potential of each VOC (Jenkin et al., 2002). Base on this simple index, a set of generic

443 intermediates (each of which is a "common representative") can be derived. Significantly reduced

444 from MCM v3.1, the resultant mechanism CRI v2 consists of 1,183 chemical reactions and 434

445 species, but is still too detailed to incorporate into most chemistry-dispersion models. To further

446 simplify CRI v2, a set of reduced derivative mechanisms (CRI v2-R1, CRI v2-R2,CRI v2-R3,CRI

447 v2-R4 and CRI v2-R5) have been developed (Watson et al., 2008). The final reduced mechanism

448 (CRI v2-R5) contains 555 chemical reactions of 196 species (including 22 VOCs) and is a useful

449 reference mechanism for air quality modelling, focusing upon ozone production. Bright et al. (2013)

450 further reduced the CRI v2-R5 and developed a Reduced Chemcial Scheme (RCS) evaluated

451 against the MCM, which includes 136 reactions of 51 species, for the application into an LES

452 model at the street canyon scale.

3.2.3 CBM

454 The Carbon Bond Mechanism (CBM-IV) was developed based on the lumped-structure

455 condensation approach for chemical reactions of VOCs with similar carbon bonds (C-CHO,C-C,

456 C=C, etc.) (Gery et al., 1989). The CBM-IV contains 81 reactions of 33 species. These species are

457 classified into four groups: explicit organic species, organic species (carbon surrogates), organic

458 species (molecular surrogates), and inorganic species (no lumping). Several other versions were

459 also developed. Heard et al. (1998) compared the CBM-IV with CBM-EX (including 204 reactions

460 and 90 species) and the reduced CBM-LEEDS (including 59 reactions of 29 species). Based on

461 CBM-IV, Zaveri and Peters (1999) developed an extended mechanism called CBM-Z (including

462 132 reactions and 52 species). CBM-IV is a popular lumped-structure mechanism but does not

463 contain some of the long-lived species and peroxy radical interactions, and has a relatively crude

464 isoprene mechanism. Due to its compactness, CBM-IV is an attractive chemical mechanism for air

465 quality modelling at the street canyon scale (e.g. Garmory et al. (2009); Kwak and Baik (2012);

466 Kwak et al. (2013); Kwak and Baik (2014)).

3.2.4 GEOS-Chem

468 GEOS-Chem (Eller et al., 2009) is a chemistry-transport model for simulating atmospheric

469 composition in the troposphere at the global scale, using the Goddard Earth Observing System

470 (GEOS) meteorological information (Abad et al., 2011). The chemical mechanism in the GEOS-

471 Chem model contains over 300 reactions of 80 species with explicit chemical schemes for main

472 anthropogenic hydrocarbons and isoprene (Bey et al., 2001). Ito et al. (2007) developed a GEOS-

473 Chem Mechanism extension (GEOSito), which includes a 490 reaction scheme of 179 species

474 accounting for a detailed representation of hydroxyl alkyl nitrates. The GEOS-Chem photochemical

475 scheme has been successfully extended to the street canyon application in terms of representing key

476   photochemical species (Kim et al., 2012). The transport time scale at the global scale is much

477   longer than that at the street canyon scale. When the global chemical scheme is adopted in a street

478   canyon, the chemical effect of those species with chemical time scales bigger than the canyon

479   dynamical residence time scale becomes less significant.

480   **3.2.5 Generalized VOCs and NO$_x$ Mechanism**

481   The Generalized VOCs and NO$_x$ Mechanism (Seinfeld and Pandis, 1998) contains 20 chemical

482   reactions of 23 species. Although this mechanism is far from comprehensive, it maintains the key

483   features of the VOC-NO$_x$ chemistry thereby providing the capablity to qualitatively analyze the

484   formation of O$_3$ through the conversion of VOCs and NO$_x$. The simple nature of this VOC-NO$_x$

485   mechanism allows it to be incorporated into most air pollution models. An early attempt to

486   implement the VOCs and NO$_x$ Mechanism into the street-canyon box modelling on the

487   investigation of O$_3$ formation can be seen from Liu and Leung (2008). The chemical processing in a

488   street canyon mainly involves the photochemistry of gas-phase species. The Generalized VOCs and

489   NO$_x$ Mechanism includes most of the key chemical processing and can be considered as a

490   promising tool to investigate the chemistry focusing on the formation of O$_3$.

491   **3.2.6 Other chemical mechanisms**

492   There are a number of other chemical mechanisms which have been applied to air pollution

493   modelling; although not widely used in the street canyon simulations to date, they have the potential

494   for future development in such applications. A chemical mechanism is often developed and

495   evaluated based on laboratory, smog chamber and field measurement data and involves a large

496   amount of chemical species and reactions to represent chemical processes in the atmosphere

497   (Dodge, 2000). There has been an enormous growth in the understanding and application of

498   chemistry in air pollution modelling. The limitation of computational resources should be

499   considered in the application of a chemical mechanism for modelling the atmospheric chemistry.

500   For grid-based air quality models, there may be millions of grid cells and therefore millions of

501 calculations for discretised differential equations are needed for each species, which requires much

502 computational time and memory storage (Stockwell et al., 2012). Several other chemical

503 mechanisms are briefly discussed below.

504 The MIM (Mainz Isoprene Mechanism) developed by Pöschl et al. (2000) is a reduced isoprene

505 degradation scheme, using a lumped molecule technique based on the Master Chemical Mechanism.

506 It includes 44 chemical reactions of 16 species, originally constructed for atmospheric modelling at

507 the global scale. Taraborrelli et al. (2009) updated the MIM into the MIM2 to represent more

508 intermediates. MIM2 includes 199 chemical reactions of 68 species and is suitable for air quality

509 modelling at both regional and global scales. The SAPRC Mechanism (SAPRC-90) was developed

510 by a research group at the (then) Statewide Air Pollution Research Center (Carter, 1990). SAPRC-

511 90 (158 chemical reactions of 54 species) is a lumped molecule mechanism, in which lumped

512 species and reactions are used to describe the degradation of organic compounds. An updated

513 version (SAPRC-99), which includes 198 reactions and 72 species, was developed by Carter

514 (2000b). The latest version of the SAPRC Mechanism (SAPRC-07) has a total of 339 reactions of

515 119 species (Carter, 2010), giving separate representation for 748 types of VOCs. The SAPRC

516 mechanisms can be used to calculate ozone reactivity scales for VOCs and predict impacts of

517 emissions on formation of secondary pollutants. The CACM (Caltech Atmospheric Chemistry

518 Mechanism) is a lumped-structure mechanism including a total of 361 reactions of 191 species

519 (Griffin et al., 2002). The inorganic chemical scheme in the CACM is based on the SAPRC99,

520 while the primary VOCs are reduced by a lumped-structure technique. CACM contains a detailed

521 chemical scheme to characterise ozone formation and formation of semi-volatile products. The

522 RACM (Regional Atmospheric Chemistry Mechanism) (Stockwell et al., 1997) consists of 237

523 reactions of 77 species revised from the Regional Acid Deposition Model (RADM2) Mechanism

524 (Stockwell et al., 1990). RACM is a lumped-molecule chemistry mechanism to describe

525 atmospheric chemistry on a regional scale. RACM has been coupled online with the RAMS model

526 (Arteta et al., 2006). RACM is capable of simulating both the lower and upper troposphere from

527 rural to urban areas. The EMEP (European Monitoring and Evaluation Programme) mechanism is

528 related to policy studies in Europe including 148 reactions of 79 species (Gross and Stockwell,

529 2003). The EMEP mechanism applies a lumped molecule technique to give representations of

530 organic compounds with a series of species of similar structure and reactivity. The EMEP

531 mechanism is highly aggregated, and is usually only applied within the atmospheric boundary layer.

532 **3.3 Comparison of chemical mechanisms**

533 Table 1 shows a comparison of chemical mechanisms varying in complexity from nearly-explicit to

534 highly-simplified. Each of the complex mechanisms contains an "inorganic mechanism"

535 considering O_x-HO_x-NO_x-CO chemistry (Emmerson and Evans, 2009), and an "organic

536 mechanism" mainly considering the degradation of VOCs. In terms of the "inorganic mechanisms",

537 there is not too much variability among different chemical mechanisms as these processes are

538 (comparatively) well understood. The NO_x-O_3 chemistry is simply extracted from the "inorganic

539 mechanism". For more complex chemical mechanisms, the main difference depends upon the

540 condensation scheme that reduces the number of VOCs and reactions involved. In principle, any

541 chemical mechanisms originally developed at different scales, from global to urban, could be

542 applied to the study of atmospheric chemistry / air pollution in street canyons (such as RCS, GEOS-

543 Chem, CBM-IV). However, the chemical processes represented by such mechanisms are inherently

544 non-linear since the chemical timescales of some species are very short and others are rather long

545 and may be variably appropriate for the typically very high NO_x levels of street canyon environment.

546 The chemical processing varies rapidly for these species with different timescales. For species with

547 chemical timescales comparable to the street canyon dynamical scale, the associated chemical

548 processes are particularly important (Bright et al., 2013). Due to the limitation of computational

549 resources, the chemical mechanism adopted in a street canyon air pollution modelling should be as

550 simple as possible to be affordable, but represents the key features of fast photochemical reactions

551 in the real atmosphere at the street canyon scale. The chemical non-linearity leads to a number of

552 difficulties for efficient coupling of chemistry with dynamic models (particularly in the street

553   canyon context whose concentrations close to the emission region may be very high), which is the

554   focus of the next section of this review.

4 Coupling dynamics and chemistry

556   The coupling between dynamics and chemistry plays a major role in air pollution modelling within

557   street canyons. Several attempts have been made to deal with both the dynamical and the chemical

558   complexity. Most long lived traffic-related pollutants (e.g. CO and VOCs) are dependent almost

559   exclusively on canyon dynamical processing, rather than chemical processing, due to their much

560   longer chemical oxidation time scales compared with the canyon dynamical residence time scale.

561   Therefore, many previous studies (e.g. Cai et al. (2008); Solazzo et al. (2011); Madalozzo et al.

562   (2014)) have only taken passive scalars into consideration, a well-established approach avoiding

563   complex chemical processing. More recently, studies have considered increasing chemical

564   reactivity and complexity; those associated with the simple NO_x-O_3 chemistry and then complex

565   chemistry involving the VOCs (shown as Table 2) will be discussed below.

4.1 Coupling with simple NO_x-O_3 chemistry

567   For relatively short-lived traffic-related pollutants (e.g. NO_2 and O_3), the assumption of non-

568   reactivity is not appropriate because their chemical time scales are comparable to, or shorter than,

569   the canyon dynamical time scale. The chemical processing of NO_x and O_3 can play a key role in

570   determining the spatial variation of these species in street canyons. Therefore, simple NO_x-O_3

571   chemistry was incorporated into street canyon dynamics models.

572   The first implementation of this approach can be found in Baker et al. (2004). They introduced the

573   NO_x-O_3 chemistry into an LES model (the Smagorinsky SGS model) based on the RAMS

574   numerical code under neutral meteorological conditions and examined the dispersion and transport

575   of chemically reactive pollutants (NO, NO_2 and O_3) inside a regular street canyon (AR=1). The

576   distributions of pollutants exhibited significant spatial variations dominated by a primary vortex in

577   the street canyon, also found by a previous field observation (Xie et al., 2003). The concept of the

578   photostationary state (PSS) defect (defined as $d_{ps}(\%) = (k_1[O_3][NO]/J_{NO_2}[NO_2]-1)\times100$, where

579   J_{NO_2}, k_1 are rate constants and $[C_i]$ represents the concentration of ith species) was introduced.

580   The PSS defect calculations showed that the chemistry was close to equilibrium within the primary

581   canyon vortex, but far from equilibrium at the canyon roof level and near traffic emissions where

582   two air parcels with distinctively different chemical composition meet. The PSS defect was shown

583   to be a useful measure of reactive mixing in and above a street canyon. Their study highlighted the

584   impact of chemical processing in the street canyon context, providing a basis for the coupling of

585   reactive species. However, only very limited chemistry was considered.

586   Grawe et al. (2007) extended the overall framework of Baker et al. (2004) to the investigation of the

587   local shading effects of windward and leeward walls on the NO_2 and O_3 concentrations. This study

588   found that kerbside NO_2 and O_3 levels exhibited over 6 ppb differences due to the presence of local

589   shading and that the magnitude of concentration differences exhibited a near-linear relationship

590   with the reduction of the NO_2 photolysis frequency in shaded regions. The shading geometry was

591   found to influence the spatial pollutant distribution within the canyon, rather than the overall

592   abundance. Their study indicated that such shading effects can be extremely significant in deep

593   street canyons. Only the effect of solar radiation on the chemical reaction rate (i.e. the NO_2

594   photolysis frequency) rather than, for example, solar heating was investigated in this study.

595   Baik et al. (2007) carried out a RANS model simulation (the RNG $k-\varepsilon$ model) coupled with

596   simple NO_x-O_3 chemistry to examine reactive pollutant dispersion within a street canyon (AR=1)

597   with bottom heating. The reaction rate constant and photolysis frequency were temperature-

598   dependent in this study (while constant values were used in Baker et al. (2004)). An oscillation of

599   the primary vortex was found in the street canyon when bottom heating was introduced and this

600   caused a significant variation in chemical species abundance. This study found that the averaged

601   temperature, NO and NO_2 concentrations had the same trend of oscillation, but opposite in sign to

602   that of the O_3 concentration. The main features of the PSS defect were found to be consistent with

603   the results of Baker et al. (2004). A budget analysis showed that advection and diffusion terms were

604   much larger than the chemical reaction term in determining the abundance of NO and NO_2, but

605   comparable to each for O_3. This budget analysis provided useful insight into the impact of chemical

606   vs. dynamical processing of each species on the overall distribution and the findings indicated that

607   the distribution of O_3 was affected by the inhomogeneous temperature in street canyons through

608   chemistry. Although this study considered the effect of heating on both the dynamical process

609   (changing the flow pattern) and chemical process (temperature-dependent chemical reaction rates),

610   it was restricted to a single street bottom heating scenario.

611   Kang et al. (2008) further investigated the effect of street bottom heating (varying the intensities of

612   heating) on flow and reactive pollutant dispersion using the same framework as Baik et al. (2007).

613   They found that the centre of the primary vortex varied with the street-bottom heating intensity and

614   thereby led to a significant variation of chemical species abundance. The evolution of the canyon-

615   averaged NO concentration under different heating intensities was found to have three types of

616   patterns (i.e. quasi-steady, oscillatory and fluctuating). The canyon-averaged concentrations tend to

617   decrease with an increase of the heating intensity. The effect of street bottom heating on the

618   concentration of O_3 through the temperature-dependent chemical reaction rates increases with

619   heating intensity, but overall this chemical processing influence was small. These findings

620   demonstrated that canyon-averaged patterns were mainly due to the dynamics influence of street-

621   bottom heating rather than the chemical influence. However, experimental data were not available

622   for the evaluation of the pollutant concentrations in the heating scenario.

623   Tong and Leung (2012) developed a RANS model (the RNG $k - \varepsilon$ turbulence model) coupled with

624   simple NO_x-O_3 photochemistry to examine the spatial characteristics of reactive pollutants and the

625   level of chemical equilibrium in idealised street canyons with aspect ratios varying from 0.5 to 8

626   under different ambient wind speeds and diurnal heating scenarios. The performance of this street

627   canyon model under bottom heating on flow and temperature fields was evaluated both

628   experimentally (Uehara et al., 2000) and numerically (i.e. Kim and Baik (2001); Xie et al. (2006)

629   and Memon et al. (2010)), and a satisfactory agreement (for normalised potential temperature and

630   horizontal velocity) was found. The entrainment of O_3 from the overlying background into the

631   canyon was found to be highly dependent upon the wind speed and canyon aspect ratio. The PSS

632   defects approached zero (reaching chemical equilibrium) more easily for the deeper street canyons.

633   They also found that the diurnal heating scenario significantly affected the pollutant exchange

634   between the canyon and overlying background through influences on vortex circulation and

635   chemical reaction rates from thermal effects.

636   Kikumoto and Ooka (2012) investigated the characteristics of reactive pollutant dispersion within a

637   regular street canyon (AR=1) by performing an LES model (the Smagorinsky SGS model) coupled

638   with a single bimolecular chemical reaction ($O_3 + NO \rightarrow product$). Their study indicated that the

639   canyon-integrated chemical reaction rate was dependent on both the product of the reactants' mean

640   concentrations, and on the correlation of their concentration fluctuations, which could be derived

641   from the LES model. RANS usually considers only the mean term and omits the correlation term

642   (which could be up to 20 % of the mean term in their study). In this aspect, LES can perform better

643   than RANS by including additional turbulent fluctuations. NO_x and O_3 had contrasting mechanisms

644   of transport and the correlation between each reactant's concentration fluctuations strongly

645   influenced the overall rate of chemical reaction between them, especially at the canyon roof level.

646   Zhong et al. (2015) adopted an LES model (the one-equation SGS model) coupled with simple

647   NO_x-O_3 photochemistry to examine the dispersion and transport of atmospheric pollutants in a deep

648   urban street canyon (AR=2). The ozone production rate inferred from NO_x-O_3 non-equilibrium was

649   found to be negative within the canyon, pointing to a systematic negative offset to ozone production

650   rates inferred by analogous field measurement approaches in environments with incomplete mixing.

651   This metric could serve to investigate the interplay of dynamics and chemistry in street canyons.

652   Reactive pollutants exhibited significant spatial variation caused by the two unsteady vortices

653   present, agreeing reasonably well with a water channel experiment (Li et al., 2008c). The deviation

654   of species abundance from chemical equilibrium for the upper vortex was found to be greater than

655 that for the lower vortex. An alternative, simplified two-box model was developed based on the

656 existence of two vortices, assuming that the deep street canyon can be described by two individual

657 well-mixed boxes with exchange between them. This two-box model can capture the significant

658 contrasts in the concentration of species inside both the lower and upper canyon vortices as

659 predicted by the LES simulation. However, this model only considered simple chemistry under

660 neutral meteorological conditions with constant (no temperature or radiation dependence) reaction

661 rates.

4.2 Coupling with complex chemistry

663 Very fast-reacting chemical species (e.g. OH, HO_2) play an important role in driving the chemical

664 cycle of VOC degradation (O_3 precursors) leading to the additional peroxy-radical mediated

665 conversion of NO to NO_2 (which is not represented by the simple NO_x-O_3 chemistry) and hence O_3

666 formation. These species, with chemical lifetimes of seconds, are primarily governed by local

667 chemical processing and their abundance varies substantially within street canyons. Complex

668 chemical mechanisms considering both NO_x and VOCs chemistry were therefore incorporated into

669 canyon dynamical models.

670 Liu and Leung (2008) implemented a one-box chemistry model using the generalized VOCs and

671 NO_x mechanism (Seinfeld and Pandis, 1998) to couple the dynamics and chemistry in street

672 canyons (AR=0.5, 1, 2). Air ventilation rates were derived from LES models for different ARs (Liu

673 et al., 2005). They found that the O_3 concentration within street canyons was dependent upon both

674 the VOCs and NO_x emission rates. When the ratio of VOCs to NO_x emission rates was higher than

675 10, the O_3 concentration could reach up to the order of 100 ppb. The emission ratio of VOCs and

676 NO_x could therefore be a useful indicator for the increase in O_3 levels in street canyons. Because

677 their study treated the whole canyon as one well-mixed box for all ARs, the model was unable to

678 reproduce the significant contrasts of pollutant concentration between the lower and upper canyon

679 which are observed experimentally.

680   Garmory et al. (2009) employed the Stochastic Field method to characterise turbulent reacting flow

681   for an investigation of the transport and dispersion of reactive scalars within a street canyon

682   (AR=1.2) adopting both simple NO_x-O_3 chemistry and the CBM-IV mechanism. The flow field was

683   based on the standard $k - \varepsilon$ model. The Stochastic Field method can be incorporated into the RANS

684   model and captures both the means and variances of pollutant abundance together with

685   consideration of segregation effects on overall reaction rates. This statistical information could not

686   be obtained from traditional RANS models. The variance of reactive pollutants was found to be

687   very high - of the order of the mean values at the canyon roof level (with strong mixing). They

688   found that for both mechanisms, there were similar predictions and no significant segregation effect

689   (the fluctuation from the mean in their study) for most major species (e.g. NO, NO_2 and O_3).

690   However, for some fast reacting chemical species (e.g. OH, HO_2 etc.), there were significant

691   segregation effects.

692   Kim et al. (2012) adopted the RNG $k - \varepsilon$ turbulence (RANS) model coupled with both simple NO_x-

693   O_3 chemistry and the GEOS-Chem photochemical scheme to investigate transport and dispersion of

694   reactive pollutants within a street canyon (AR=1). An online photolysis rate calculation module was

695   applied to account for the surface heating effect of diurnal solar radiation on the photolysis rate

696   coefficients. The NO concentrations predicted from simple NO_x-O_3 chemistry had a difference up to

697   100 ppb (i.e. the relative error was about 20%~30%) compared to those of Baker et al. (2004).

698   They attributed this discrepancy to the different turbulence models, RANS in this study and LES in

699   Baker et al. (2004). Compared with field measurements, the model over-predicted the NO

700   concentration by a factor of 3. This big relative error in NO concentration was expected to decrease

701   as NO_x emissions became lower. There was an evidence of a significant difference in predicted O_3

702   concentration between complex photochemistry and the simple NO_x-O_3 chemistry, indicating the

703   importance of additional formation of O_3 through VOC oxidation processes. This study highlighted

704   the importance of photochemistry in controlling the concentration of oxidation products (e.g. NO_2

705   and O_3) within street canyons.

706   Kwak and Baik (2012) employed the RNG $k - \varepsilon$ turbulence (RANS) model coupled with the CBM-

707   IV mechanism to explore reactive pollutant dispersion within idealised street canyons (AR=1) and

708   to investigate O_3 sensitivity to NO_x and VOCs emissions. According to the dispersion

709   characteristics of NO, NO_2 and O_3 in the simple NO_x-O_3 chemistry model, the dispersion of species

710   in this simulation were identified and classified into three types, denoted by NO-type, NO_2-type and

711   O_3-type, with maximum concentrations near the bottom of the street canyon, close to the centre of

712   the street canyon, and above the street canyon, respectively. The dispersion type of a reactive

713   species was found to be dependent upon the ratio of VOCs to NO_x emission rates. Their study

714   showed that the OH concentration increased with an increase in the VOCs to NO_x emission ratio,

715   indicating an important role for OH in determining the dispersion type. The O_3 concentration was

716   found to be negatively correlated with NO_x emissions but weakly correlated with VOCs emissions.

717   This was possibly due to the high NO-to-NO_2 ratio in the street canyon, where the NO titration of

718   O_3 was more pronounced compared to NO_2 photolysis. Their study provided a good understanding

719   of the dispersion characteristics of reactive species and the O_3 sensitivity to a range of NO_x and

720   VOCs emission scenarios for the street canyon.

721   Kwak et al. (2013) implemented the same RANS model and chemical mechanism as those adopted

722   by Kwak and Baik (2012), but focusing on the photochemical evolution of reactive species within

723   street canyons (AR=1,2). The concept of photochemical ages (defined as the time-integrated

724   exposures of an air parcel to O_3 and OH respectively) was introduced to represent the O_3 and OH

725   oxidation processes, and normalised by their respective background ages. The normalised

726   photochemical ages, ranging from 0 (emission characteristics) to 1 (background characteristics),

727   had the advantage of avoiding the uncertainty of calculating the averaged O_3 and OH concentrations

728   individually. They found that both O_3 and OH oxidation processes were of importance for the

729   photochemistry at the canyon-scale. Overall, O_3 was chemically reduced in the lower part, but

730   chemically produced in the upper part of the deep street canyon (AR=2). This interesting finding

731   indicated that O_3 was not always chemically reduced in a street canyon. From a sensitivity analysis,

732   the concentration of O_3 was found to be weakly sensitive to the wind speed. An increase of O_3

733   concentration was found with an increase in the ratio of VOCs to NO_x emissions, consistent with

734   Liu and Leung (2008). This finding implied that the O_3 concentration was more sensitive to changes

735   of emissions than to changes in dynamics. In terms of characterizing O_3 and OH chemical

736   processing, the photochemical age concept was applicable to characterise the photochemistry at the

737   street-canyon scale, and could potentially be extended to the neighbourhood scale.

738   Bright et al. (2013) employed an LES model (the Smagorinsky SGS model) coupled with a

739   Reduced Chemcial Scheme (RCS) and the simple NO_x-O_3 photochemistry to investigate the effects

740   of mixing and chemcial processing on the atmospheric composition in a urban street canyon

741   (AR=1). A one-box chemistry model was also adopted for the comparison with the LES coupled

742   chemistry model to assese the effect of dynamic and chemical processing. The LES coupled

743   chemistry model was found to underestimate the concentration of NO_x, OH and HO_2, but

744   overestimate the concentration of O_3 averaged over the whole canyon compared to the one-box

745   chemistry model. The segregation effect caused by the incomplete mixing was found to reduce the

746   overall canyon-averaged reaction rate and be responsible for the spatial inhomogeneity of reactive

747   species. It was shown that the RCS scheme predicted higher levels of NO_2 and O_3, but a lower level

748   of NO compared with the simple NO_x-O_3 photochemistry. This can be explained by the additional

749   NO to NO_2 conversion through VOCs oxidation chemistry present in the RCS. Their study provided

750   a better understanding of the atmospheric "pre-processing" of emissions from the street canyon

751   prior to release to the wider overlying background.

752   Kwak and Baik (2014) adopted the RNG $k-\varepsilon$ turbulence (RANS) model coupled with the CBM-

753   IV mechanism to examine the removal and entrainment of reactive pollutants at the canyon roof

754   level via the diurnal variation in NO_x and O_3 exchange between the 2D street canyon (AR=1) and

755   the overlying background air. In the morning, two conter-rotating vortices were found in the street

756   canyon because the heating of downwind wall was stronger than that of upwind wall. Therefore, the

757   NO_x and O_3 exchange was found to be dominated by turbulent flow. However, in the afternoon,

758   only one intensified primary vortex was found because heating of the downwind wall was lower

759   than that of the upwind wall. The turbulent flow became comparable to the mean flow in terms of

760   the NO_x and O_3 exchange. Their findings indicated that the exchange veloctities were strongly

761   dependent on both the flow pattern induced by surface heating and the photochemistry in the street

762   canyons (Bright et al., 2013).

763   Zhong et al. (2014) implemented photochemical box models to investigate the segregation effects of

764   heterogeneous emissions on O_3 levels in idealised urban street canyons and evaluate the associated

765   uncertainty when grid-averaged emissions were adopted. The chemical mechanism applied was the

766   RCS developed by Bright et al. (2013). Chemical effects arising from the heterogeneity of

767   emissions and dynamic effects represented by the exchange velocity (derived from CFD models)

768   between the canyon and the overlying background on the O_3 levels were extensively investigated.

769   The O_3 levels within street canyons were found to be strongly linked to the segregation of spatially

770   varying emissions and to be balanced by both chemistry and dynamics. Their study indentified a

771   straightforward approach to consider the effects of both chemistry and dynamics using box models

772   with a wide range of emission scenarios. However, this study was restricted to two boxes

773   representing two idealised street canyons (totally segregated) with emission heterogeneity.

774   Park et al. (2015) implemented the RNG $k-\varepsilon$ turbulence (RANS) model coupled with the GEOS-

775   Chem photochemical scheme (also used in the study by Kim et al. (2012)) to investigate the effect

776   of canyon aspect ratio on pollutant dispersion in street canyons. One vortex was observed for

777   canyons with $1 \le AR \le 1.6$, while two vortices were found for canyons where $1.6 < AR \le 2$. At the

778   street bottom, there was a significant contrast in the flow pattern between those two types of

779   canyons. For cases with a low ratio of VOCs to NO_x emission, the O_3 concentrations in street

780   canyons were much lower than those in the overlying background. This was attributed to the

781   titration of O_3 by high levels of NO. For cases with higher ratio of VOCs to NO_x emission, O_3 in the

782   lower canyon was slightly titrated by NO, but in the upper canyon O_3 was formed by NO_2

783 photolysis following VOCs oxidation processes. The ratio of VOCs to NO_x emission was an
784 important indicator in determining the street-level O_3 concentration.

785 Simple NO_x-O_3 chemistry plays an important role in the street canyon chemistry. The NO_x-O_3
786 photostationary state defect is a useful measure of reacting mixing in the street canyon environment
787 (Baker et al., 2004). Due to its simple nature, simple NO_x-O_3 chemistry can easily be coupled with
788 either LES or RANS models. Complex chemical mechanisms involve detailed VOCs oxidation
789 reactions driven by fast radicals (e.g. OH and HO_2), leading to additional NO to NO_2 conversion
790 (non-O_3). In this sense, complex chemical mechanisms are more realistic than simple NO_x-O_3
791 chemistry. However, due to large amounts of chemical reactions and species, more efforts need to
792 be spent when incorporating a complex chemical mechanism into numerical models. LES models
793 perform better in terms of the turbulent mixing of pollutants within street canyons, but require much
794 more computational cost than RANS. LES can be used to investigate the detailed mechanism of
795 pollutant dispersion and transport (e.g. Baker et al. (2004); Kikumoto and Ooka (2012); Bright et al.
796 (2013); Zhong et al. (2015)), with higher (e.g. for NO_x) or lower (e.g. for O_3, OH and HO_2)
797 concentrations in the canyon than those at the overlying background. RANS provides the capability
798 to run quickly for a few scenarios, such as varying intensities of street heating ambient wind speeds,
799 canyon aspect ratios and emissions (e.g. Kang et al. (2008); Tong and Leung (2012); Kwak and
800 Baik (2012); Kwak et al. (2013); Park et al. (2015)). With simplified parameterisation of street
801 canyon air ventilation, box models can be run very quickly for a series of wind conditions and
802 emission scenarios (e.g. Liu and Leung (2008); Zhong et al. (2014)) so that complex chemical
803 mechanisms are affordable for street canyon chemistry modelling.

804 ## 5 Modelling concerns

805 ### 5.1 Street canyon geometry

806 Street canyon geometry plays an important role in determining the flow patterns and pollutant
807 dispersion within street canyons. The AR (aspect ratio) influences the number of primary re-

808   circulations formed inside a street canyon and the higher the AR is, the larger the number of

809   primary re-circulations will be. A single primary vortex is formed within regular street canyons (e.g.

810   Baker et al. (2004)) and multiply primary vortices are formed within deep street canyons (e.g. Li et

811   al. (2009); Murena (2012); Zhong et al. (2015)). The vortices formed in street canyons influence

812   pollutant dispersion behaviour and air ventilation. There is evidence that higher concentrations of

813   pollutants are found in street canyons with higher aspect ratios. Liu et al. (2004) showed that the

814   percentages of pollutants residing inside street canyons (compared to the total pollutants in the

815   computational domain) with aspect ratios of 0.5, 1.0 and 2.0 were about 95%, 97% and 99%,

816   respectively. Li et al. (2009) found that there was a higher pollutant accumulation at the ground

817   level in the street canyon with AR=5 compared with that with AR=3. This could be driven by the

818   very low wind speed at ground level, which slowed the dispersion of ground-level pollutant. This

819   finding was consistent with field measurements in a deep street canyon with AR=5.7 (Murena and

820   Favale (2007); Murena et al. (2008)), which showed that the concentration at pedestrian level in the

821   deep street canyon could be up to three times that in a regular street canyon with AR=1. The shape

822   of the roofs also influences the turbulence at the canyon roof level and hence the dispersion of

823   pollutants. Pitched roofs are expected to induce more energetic eddies and have more turbulent

824   exchange of pollutants at the canyon roof level than flat roofs (Louka et al., 2000).

825   **5.2 Meteorological conditions**

826   Meteorological conditions (e.g. ambient wind and solar radiation) significantly affect the flow and

827   dispersion of reactive pollutants in street canyons. The ambient wind speed plays an important role

828   in the formation and intensity of primary vortices thereby determining pollutant retention time in

829   the canyon, while its direction influences the number and shape of such vortices (Baik et al., 2003).

830   Nazridoust and Ahmadi (2006) showed that turbulence intensity within street canyon increased with

831   the ambient wind speed. As pollutant dispersion is strongly dependent on the turbulence in the street

832   canyon, higher wind speeds lead to stronger street-canyon turbulent flow and thereby making it

833   more effective for pollutants to be removed from the street canyon. This behaviour was also found

834   by Huang et al. (2000). Small secondary vortices were formed at the corner of the street canyon

835   under low wind speed conditions, but would disappear under higher wind speed conditions.

836   Michioka and Sato (2012) examined the effect of incoming turbulent structure on the canyon flow

837   and pollutant dispersion. The pollutant concentration in the street canyon decreased with an increase

838   in the incoming turbulent intensity. Changes in ambient wind direction significantly affected the

839   recirculation pattern in the canyon (Soulhac et al. (2008); Soulhac and Salizzoni (2010); Blackman

840   et al. (2015)) and thereby influenced pollutant dispersion. Pollutant dispersion was more effective

841   for an oblique flow than a perpendicular flow, as found in field measurements by Kumar et al.

842   (2008). In the presence of solar radiation, surfaces of the ground and buildings are heated, which

843   will influence the atmospheric stability and (to an extent) the chemical reaction rate constants (e.g.

844   Baik et al. (2007)). The flow field and pollutant dispersion in street canyons can be significantly

845   affected by additional thermally induced vortices. The combination of mechanically induced

846   vortices (from wind) and the thermally induced vortices (from heating) adds further complexity

847   (Xie et al., 2005). Cai (2012a) and Cai (2012b) identified two characteristic heating scenarios in a

848   street canyon: the assisting case (both roof and upwind wall heating) and the opposing case (both

849   roof and downwind wall heating) depending on the direction of the thermal-driven flow in relation

850   to the wind-driven circulation. Li et al. (2012) investigated the effect of ground heating on flow and

851   pollutant dispersion in street canyons with AR=0.5,1, and 2, and found that the flow and pollutant

852   patterns underwent significant changes. In general, ground heating enhanced the mixing of

853   pollutants in street canyons.

854   **5.3 Emissions**

855   Traffic is considered to be the major source of emissions in urban street canyons. Vehicle emissions

856   can be derived based on traffic information and the emission factors of each class of vehicle.

857   Typically, traffic information contains vehicle fleet composition, average speeds and traffic

858   volumes. For roads equipped with automatic traffic counts, this traffic information can be easily

859   obtained. The emission rates for each emitted pollutant (e.g. CO, VOCs, NO_x) can serve as the input

860   for air pollution modelling (Boddy et al., 2005). Xie et al. (2009) compared a series of measured

861   data for the CO concentration and the traffic volumes under the same wind direction and a linear

862   relationship between them was found, as CO is a relatively inert chemical species (on the canyon

863   timescale). The NO_2/NO_x emission ratio by volume from vehicles has typically been applied as 1/11

864   (e.g. Baker et al. (2004)) or 1/10 (e.g. Bright et al. (2013)), reflecting that the fraction of directly

865   emitted NO_2 was much lower than that of NO from vehicles, making the production of NO_2 through

866   the NO titration reaction more important. However, there is evidence of recent increases in

867   NO_2/NO_x emission ratios, up to about 25 % (Carslaw and Rhys-Tyler, 2013). The O_3 concentration

868   within street canyons is dependent upon both VOCs and NO_x emission rates. O_3 was found to be

869   more sensitive to changes in emissions rather than to changes in dynamics. The anticipated trend

870   over 2005-2020 in VOCs to NO_x emission rates, based upon scenarios of UK fleet composition

871   projections (NAEI, 2003) and UK Road Vehicle Emission Factors (Boulter et al., 2009) suggested

872   that although both VOCs to NO_x emissions have (and are expected to) generally decrease with time,

873   the O_3 concentration in street canyons will have slightly increased due to these effects - although

874   other changes (e.g. in background ozone) may dominate the absolute observed levels / trends.

875   Finally, it is important to note that real-world emissions may vary substantially from both vehicle

876   type-approval data, and from inventory values - e.g. Grimmond et al. (1998).

877   5.4 Chemical transformation of pollutants

878   Emissions from vehicles may be reactive, changing dramatically the chemical composition of the

879   atmosphere in street canyon environments. Such emissions undergo chemical transformation to

880   varying extents within the recirculation driven by the canyon flow before their escape into the

881   overlying atmosphere. Such chemical transformations can occur on a wide range of timescales,

882   posing difficulty for computationally efficiently handling of chemical processes when these must be

883   coupled with dynamics at the street canyon scale. The choice of chemical mechanism employed

884   must be considered depending on the complexity of chemistry involved, and the application. For

885   street canyon modelling, numerical issues arise because the governing equation systems are highly

886   nonlinear, and extremely stiff (Verwer and Simpson, 1995) especially when highly reactive species

887   (such as OH and HO$_2$) are considered alongside longer-lived VOCs. If diurnal heat (temperature)

888   effects on the chemistry are included, extra complexity arises since most reaction rates and (to a

889   lesser extent) photolysis frequencies are influenced by changes in temperature (Kim et al., 2012).

890   Particular attention should be paid to the handling of fast-reacting species, e.g. applying a

891   sufficiently short integration time interval (Bright et al., 2013). Also, in the regions close to the

892   emisison source and to the shear layer (which must be well-resolved), negative values of

893   concentrations may occur in numerical simulations, due to the presence of high concentration

894   gradients, which in addition to being implausible affect the stability of the stiff chemical system

895   (Alexandrov et al., 1997). Such negative concentrations indicate unsatisfactory convergence or

896   insufficiently short integration timescales.

897   **6 Conclusions**

898   This article presents a review of air pollution modelling within street canyons, focusing on the

899   coupling of dynamics and chemistry. For dynamics, the CFD technique has become a powerful

900   numerical tool, mainly including the RANS and LES models. RANS models are, by their nature, a

901   steady-state methodology while LES models can handle the unsteadiness and intermittency of the

902   canyon flow and retrieve transient structures of turbulence in street canyons. The choice between

903   approaches depends on the computational cost, the accuracy required and hence the application. A

904   parameter (i.e. 'exchange velocity') representing the overall integrated effect of dynamics in street

905   canyons provides capablity to handle relatively complex chemistry in practical applications. The

906   representation of the chemistry (i.e. the chemical mechanism) for air pollution modelling is also an

907   important component for this coupling approach. For short-lived traffic-related pollutants (e.g. NO$_2$

908   and O$_3$), chemical time scales are comparable to the canyon dynamic time scale. The chemical

909   processing of NO$_x$ and O$_3$ can play a key role in determining the spatial variation of these species in

910   street canyons. Simple NO$_x$-O$_3$ chemistry only accounts for the O$_3$ chemistry changes driven by

911   NO_x, without consideration of VOCs processing. More complex chemistry involving VOCs

912   (resulting in the additional conversion of NO to NO_2 that cannot be represented by simple NO_x-O_3

913   chemistry) should be considered for application to the real urban atmosphere. A wide range of

914   chemical mechanisms with varying complexity considering both NO_x and VOCs chemistry can

915   potentially be adopted in street canyon simulations. A variety of factors should be considered such

916   as street canyon geometry, meteorological conditions, emissions and chemical transformation of

917   pollutants. Modelling air pollution within a street canyon requires state-of-the-art dynamic models

918   coupled with high-quality chemical mechanisms to simulate the concentrations and spatial patterns

919   of key atmospheric chemical species, providing reference information regarding air quality inside

920   street canyons for policy-makers in support of decision making for traffic policy and urban planning.

921   Future directions in this area could be: 1) Development of a widely accepted procedure for

922   representation of street-canyon dynamics; 2) Clear guidance as to the level of detail of

923   photochemistry required for different street canyon applications, and the consequences for

924   systematic over/under-prediction of reactive species abundance arising from this; 3) Application of

925   RANS models coupled with complex chemical mechanisms focusing on a variety of factors for

926   practical application; 4) Application of Large Eddy Simulations (LES) coupled with complex

927   chemical mechanisms focusing on the detailed interaction of dynamic and chemical processing in

928   street canyons; 5) Box models with more comprehensive / complex chemical mechanisms focusing

929   on the testing of simplified dynamic parameters (e.g. exchange velocities), in particular to allow

930   efficient exploration of chemical emission scenarios; 6) Thermal effects (e.g. caused by solar

931   radiation) on both dynamics and chemical processing; 7) Effects of more complex urban

932   configurations (e.g. intersections, irregular buildings, parking spaces and trees) on both the

933   dynamics and the associated chemical processing; 8) Near-field evolution of traffic-derived

934   particulate matter, including both chemical and physical (e.g. evaporation, condensation) effects; 9)

935   CFD-chemistry modelling coupled with mesoscale meteorological and chemistry-transport models

936   for the investigation of reactive pollutant dispersion in urban areas (Kwak et al., 2015).

940

941

942

943

944

945 **Table 1 Comparison of chemical mechanisms for air quality modelling**

Full name of chemical mechanisms	Reduction type	Reference	Versions	Reaction NO.	Species NO.	Applied scale
Master Chemical Mechanisms	Near-explicit	Derwent et al. (1998)	MCM v1.0	>7,100	>2,400	Troposphere
		Whitehouse et al. (2004)	MCM v2.0	10,763	3,487	
		Saunders et al. (2003)	MCM v3.0	12,737	>4351	
		Pinho et al. (2007)	MCM v3.1	~13,500	~5,900	
		Jenkin et al. (2012)	MCM v3.2	~17,000	~6,700	
Common Representative	LM	Jenkin et al. (2008)	CRI v2	1183	434	Troposphere
Intermediates Mechanism		Watson et al. (2008)	CRI v2-R1	1012	373	
			CRI v2-R2	988	352	
			CRI v2-R3	882	296	
			CRI v2-R4	643	219	
			CRI v2-R5	555	196	
		Bright et al. (2013)	RCS	136	51	Urban
Carbon Bond Mechanism	LS	Gery et al. (1989)	CBM-IV	81	33	Urban/Regional
		Heard et al. (1998)	CBM-EX	204	90	
		Heard et al. (1998)	CBM-LEEDS	59	29	
		Zaveri and Peters (1999)	CBM-Z	132	52	
Goddard Earth	/	Eller et al. (2009)	GEOS-Chem	300	80	Global

Observing System-Chemistry		Ito et al. (2007)	GEOSito	490	179	
Generalized VOCs and NO$_x$ Mechanism	/	(Seinfeld and Pandis, 1998)	/	20	23	Urban
Mainz Isoprene Mechanism	LM	Pöschl et al. (2000)	MIM	44	16	Regional/Global
		Taraborrelli et al. (2009)	MIM2	199	68	
Statewide Air Pollution Research Center	LM	Carter (1990)	SAPRC-90	158	54	Urban
		Carter (2000b)	SAPRC-99	198	72	
		Carter (2010)	SAPRC-07	339	119	
Caltech Atmospheric Chemistry Mechanism	LS	Griffin et al. (2002)	CACM	361	191	Urban
Regional Atmospheric Chemistry Mechanism	LM	Stockwell et al. (1997)	RACM	237	77	Regional
	LM	Stockwell et al. (1990)	RADM2	158	63	
European Monitoring and Evaluation Programme	LM	Gross and Stockwell (2003)	EMEP	148	79	Regional
NO$_x$-O$_3$ chemistry	/	Smagorinsky (1963)	/	3	5	Urban

Note: LS denotes the lumped structure reduction technique. LM denotes the lumped molecule reduction technique.

946

947 **Table 2 Comparison of selected studies coupling dynamics and chemistry in street canyons**

Reference	Research model	AR (H/W)	Vortex No.	Chemical mechanism	Remarks
Baker et al. (2004)	LES	1	1	NO$_x$-O$_3$ chemistry	*Significant spatial variations of NOx and O$_3$ *Introduction of the photostationary state defect
Grawe et al. (2007)	LES	1	1	NO$_x$-O$_3$ chemistry	*Shading effect *A near-linear relationship between concentration differences and the reduction of the NO$_2$ photolysis rate
Baik et al. (2007)	RANS	1	1	NO$_x$-O$_3$ chemistry	*Street bottom heating scenario *Budget analysis of the advection, diffusion and chemical reaction term
Kang et al. (2008)	RANS	1	1	NO$_x$-O$_3$ chemistry	* Varying the intensities of street bottom heating *Significant change in pattern of the flow and pollutant dispersion
Tong and Leung (2012)	RANS	0.5-8	Varying	NO$_x$-O$_3$ chemistry	* Different diurnal heating scenarios * Varying canyon aspect ratios
Kikumoto and Ooka (2012)	LES	1	1	NO$_x$-O$_3$ chemistry	* Contrasting transport mechanism for NO$_x$ and O$_3$ * Correlation of concentration fluctuations
Zhong et al. (2015)	LES	2	2	NO$_x$-O$_3$ chemistry	*Two-box model *Inferred O$_3$ production rates
Liu and Leung (2008)	Box model	0.5,1,2	Box	Generalized VOCs-NO$_x$ mechanism	* O$_3$ sensitivity to the NO$_x$ and VOCs emissions * One-box chemsitry model * Parameteriaed air ventilation rate
Garmory et al. (2009)	RANS	1.2	1	NO$_x$-O$_3$ chemistry and CBM-IV	* Field Monte Carlo method for turbulent reacting flow simulation * Segregation effect and micro-mixing
Kim et al. (2012)	RANS	1	1	NO$_x$-O$_3$ chemistry	* An online photolysis rate calculation module

				and GEOS-Chem	* Consideration of dry deposition
Kwak and Baik (2012)	RANS	1	1	CBM-IV	* Dispersion type of reactive species * O_3 sensitivity to the NO_x and VOCs emissions
Kwak et al. (2013)	RANS	1 , 2	1 -,2	CBM-IV	* Photochemical evolution * O_3 and OH oxidation processes
Bright et al. (2013)	LES, Box model	1	1	NO_x-O_3 chemistry and RCS	* Segregation effect * Comparion with box model * Atmospheric "pre-processing"
Kwak and Baik (2014)	RANS	1	1 or 2	CBM-IV	* Surface heating *Diurnal variation of NO_x and O_3 exchange
Zhong et al. (2014)	Box model	1	Box	RCS	* Segregation effect * Simple box models * Considering both chemical and dynamical effects
Park et al. (2015)	RANS	1-2	1-2	GEOS-Chem	* Varying canyon aspect ratios *Varying ratios of VOCs emission to NO_x emission

948

949

950

951

References:

ABAD, G. G., ALLEN, N. D. C., BERNATH, P. F., BOONE, C. D., MCLEOD, S. D., MANNEY, G. L., TOON, G. C., CAROUGE, C., WANG, Y., WU, S., BARKLEY, M. P., PALMER, P. I., XIAO, Y. & FU, T. M. 2011. Ethane, ethyne and carbon monoxide concentrations in the upper troposphere and lower stratosphere from ACE and GEOS-Chem: a comparison study. *Atmospheric Chemistry and Physics,* 11**,** 9927-9941.

AHMAD, K., KHARE, M. & CHAUDHRY, K. K. 2005. Wind tunnel simulation studies on dispersion at urban street canyons and intersections - a review. *Journal of Wind Engineering and Industrial Aerodynamics,* 93**,** 697-717.

ALEXANDROV, A., SAMEH, A., SIDDIQUE, Y. & ZLATEV, Z. 1997. Numerical integration of chemical ODE problems arising in air pollution models. *Environmental Modeling & Assessment,* 2**,** 365-377.

BADY, M., KATO, S., TAKAHASHI, T. & HUANG, H. An experimental investigation of the wind environment and air quality within a densely populated urban street canyon. *Journal of Wind Engineering and Industrial Aerodynamics,* 99**,** 857-867.

BAIK, J.-J., KANG, Y.-S. & KIM, J.-J. 2007. Modeling reactive pollutant dispersion in an urban street canyon. *Atmospheric Environment,* 41**,** 934-949.

BAIK, J. J. & KIM, J. J. 1999. A numerical study of flow and pollutant dispersion characteristics in urban street canyons. *Journal of Applied Meteorology,* 38**,** 1576-1589.

BAIK, J. J., KIM, J. J. & FERNANDO, H. J. S. 2003. A CFD model for simulating urban flow and dispersion. *Journal of Applied Meteorology,* 42**,** 1636-1648.

BAIK, J. J., PARK, R. S., CHUN, H. Y. & KIM, J. J. 2000. A laboratory model of urban street-canyon flows. *Journal of Applied Meteorology,* 39**,** 1592-1600.

BAKER, J., WALKER, H. L. & CAI, X. M. 2004. A study of the dispersion and transport of reactive pollutants in and above street canyons - a large eddy simulation. *Atmospheric Environment,* 38**,** 6883-6892.

BARLOW, J. F., HARMAN, I. N. & BELCHER, S. E. 2004. Scalar fluxes from urban street canyons. Part I: Laboratory simulation. *Boundary-Layer Meteorology,* 113**,** 369-385.

BERKOWICZ, R. 2000. OSPM - A parameterised street pollution model. *Environmental Monitoring and Assessment,* 65**,** 323-331.

BEY, I., JACOB, D. J., YANTOSCA, R. M., LOGAN, J. A., FIELD, B. D., FIORE, A. M., LI, Q. B., LIU, H. G. Y., MICKLEY, L. J. & SCHULTZ, M. G. 2001. Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *Journal of Geophysical Research-Atmospheres,* 106**,** 23073-23095.

BLACKMAN, K., PERRET, L., SAVORY, E. & PIQUET, T. 2015. Field and wind tunnel modeling of an idealized street canyon flow. *Atmospheric Environment,* 106**,** 139-153.

BLOSS, C., WAGNER, V., JENKIN, M. E., VOLKAMER, R., BLOSS, W. J., LEE, J. D., HEARD, D. E., WIRTZ, K., MARTIN-REVIEJO, M., REA, G., WENGER, J. C. & PILLING, M. J. 2005. Development of a detailed chemical mechanism (MCMv3.1) for the atmospheric oxidation of aromatic hydrocarbons. *Atmospheric Chemistry and Physics,* 5**,** 641-664.

BODDY, J. W. D., SMALLEY, R. J., DIXON, N. S., TATE, J. E. & TOMLIN, A. S. 2005. The spatial variability in concentrations of a traffic-related pollutant in two street canyons in York, UK - Part I: The influence of background winds. *Atmospheric Environment,* 39**,** 3147-3161.

BOULTER, P. G., BARLOW, T. J., LATHAM, S. & MCCRAE, I. S. 2009. Emission Factors 2009: Report 1 - a review of methods for determining hot exhaust emission factors for road vehicles. *TRL: Wokingham.*

BRIGHT, V. B., BLOSS, W. J. & CAI, X. M. 2013. Urban street canyons: Coupling dynamics, chemistry and within-canyon chemical processing of emissions. *Atmospheric Environment,* 68**,** 127-142.

BROWN, M. J., LAWSON JR., R. E., DECROIX, D. S. & LEE, R. L. 2000. MEAN FLOW AND TURBULENCE MEASUREMENTS AROUND A 2-D ARRAY OF BUILDINGS IN A WIND TUNNEL. *Presented at 11th Joint Conference on the Applications of Air Pollution Meteorology with the AWMA,* Long Beach, CA**,** January 9-14.

BUCKLAND, A. T. 1998. Validation of a street canyon model in two cities. *Environmental Monitoring and Assessment,* 52**,** 255-267.

CAI, X. 2012a. Effects of differential wall heating in street canyons on dispersion and ventilation characteristics of a passive scalar. *Atmospheric Environment,* 51**,** 268-277.

CAI, X. M. 2012b. Effects of Wall Heating on Flow Characteristics in a Street Canyon. *Boundary-Layer Meteorology,* 142**,** 443-467.

CAI, X. M., BARLOW, J. F. & BELCHER, S. E. 2008. Dispersion and transfer of passive scalars in and above street canyons - Large-eddy simulations. *Atmospheric Environment,* 42**,** 5885-5895.

CARSLAW, D. & RHYS-TYLER, G. 2013. Remote sensing of NO_2 exhaust emissions from road vehicles. *A report to the City of London Corporation and London Borough of Ealing.*

CARTER, W. P. L. 1990. A DETAILED MECHANISM FOR THE GAS-PHASE ATMOSPHERIC REACTIONS OF ORGANIC-COMPOUNDS. *Atmospheric Environment Part a-General Topics,* 24**,** 481-518.

CARTER, W. P. L. 2000b. Implementation of the SAPRC-99 chemical mechanism into the Models-3 Framework. *Report to the US Environmental Agency,* 29 January 2000.

CARTER, W. P. L. 2010. Development of a condensed SAPRC-07 chemical mechanism. *Atmospheric Environment,* 44**,** 5336-5345.

CATON, F., BRITTER, R. E. & DALZIEL, S. 2003. Dispersion mechanisms in a street canyon. *Atmospheric Environment,* 37**,** 693-702.

CHAN, T. L., DONG, G., LEUNG, C. W., CHEUNG, C. S. & HUNG, W. T. 2002. Validation of a two-dimensional pollutant dispersion model in an isolated street canyon. *Atmospheric Environment,* 36**,** 861-872.

CHANG, C. H. 2006. Computational fluid dynamics simulation of concentration distributions from a point source in the urban street canyons. *Journal of Aerospace Engineering,* 19**,** 80-86.

CHANG, C. H. & MERONEY, R. N. 2001. Numerical and physical modeling of bluff body flow and dispersion in urban street canyons. *Journal of Wind Engineering and Industrial Aerodynamics,* 89**,** 1325-1334.

CHENG, W. C. & LIU, C.-H. 2011. Large-Eddy Simulation of Flow and Pollutant Transports in and Above Two-Dimensional Idealized Street Canyons. *Boundary-Layer Meteorology,* 139**,** 411-437.

CHENG, W. C., LIU, C.-H. & LEUNG, D. Y. C. 2008. Computational formulation for the evaluation of street canyon ventilation and pollutant removal performance. *Atmospheric Environment,* 42**,** 9041-9051.

CHENG, Y., LIEN, F. S., YEE, E. & SINCLAIR, R. 2003. A comparison of large Eddy simulations with a standard k-epsilon Reynolds-averaged Navier-Stokes model for the prediction of a fully developed turbulent flow over a matrix of cubes. *Journal of Wind Engineering and Industrial Aerodynamics,* 91**,** 1301-1328.

CHUNG, T. N. H. & LIU, C.-H. 2013. On the Mechanism of Air Pollutant Removal in Two-Dimensional Idealized Street Canyons: A Large-Eddy Simulation Approach. *Boundary-Layer Meteorology,* 148**,** 241-253.

CUI, Z. Q., CAI, X. M. & BAKER, C. J. 2004. Large-eddy simulation of turbulent flow in a street canyon. *Quarterly Journal of the Royal Meteorological Society,* 130**,** 1373-1394.

DEJOAN, A., SANTIAGO, J. L., MARTILLI, A., MARTIN, F. & PINELLI, A. 2010. Comparison Between Large-Eddy Simulation and Reynolds-Averaged Navier-Stokes Computations for the MUST Field Experiment. Part II: Effects of Incident Wind Angle Deviation on the Mean Flow and Plume Dispersion. *Boundary-Layer Meteorology,* 135**,** 133-150.

DEPAUL, F. T. & SHEIH, C. M. 1986. MEASUREMENTS OF WIND VELOCITIES IN A STREET CANYON. *Atmospheric Environment,* 20**,** 455-459.

DERWENT, R. G., JENKIN, M. E., SAUNDERS, S. M. & PILLING, M. J. 1998. Photochemical ozone creation potentials for organic compounds in northwest Europe calculated with a master chemical mechanism. *Atmospheric Environment,* 32**,** 2429-2441.

DODGE, M. C. 2000. Chemical oxidant mechanisms for air quality modeling: critical review. *Atmospheric Environment,* 34**,** 2103-2130.

ELLER, P., SINGH, K., SANDU, A., BOWMAN, K., HENZE, D. K. & LEE, M. 2009. Implementation and evaluation of an array of chemical solvers in the Global Chemical Transport Model GEOS-Chem. *Geoscientific Model Development,* 2**,** 89-96.

EMMERSON, K. M. & EVANS, M. J. 2009. Comparison of tropospheric gas-phase chemistry schemes for use within global models. *Atmospheric Chemistry and Physics,* 9**,** 1831-1845.

GARMORY, A., KIM, I. S., BRITTER, R. E. & MASTORAKOS, E. 2009. Simulations of the dispersion of reactive pollutants in a street canyon, considering different chemical mechanisms and micromixing. *Atmospheric Environment,* 43**,** 4670-4680.

GERMANO, M., PIOMELLI, U., MOIN, P. & CABOT, W. H. 1991. A DYNAMIC SUBGRID-SCALE EDDY VISCOSITY MODEL. *Physics of Fluids a-Fluid Dynamics,* 3**,** 1760-1765.

GERY, M. W., WHITTEN, G. Z., KILLUS, J. P. & DODGE, M. C. 1989. A photochemical kinetics mechanism for urban and regional scale computer modeling. *Journal of Geophysical Research,* 94**,** 12925-12956.

GRAWE, D., CAI, X.-M. & HARRISON, R. M. 2007. Large eddy simulation of shading effects on NO2 and O3 concentrations within an idealised street canyon. *Atmospheric Environment,* 41**,** 7304-7314.

GRIFFIN, R. J., DABDUB, D. & SEINFELD, J. H. 2002. Secondary organic aerosol - 1. Atmospheric chemical mechanism for production of molecular constituents. *Journal of Geophysical Research-Atmospheres,* 107.

GRIMMOND, C. S. B., KING, T. S., ROTH, M. & OKE, T. R. 1998. Aerodynamic roughness of urban areas derived from wind observations. *Boundary-Layer Meteorology,* 89**,** 1-24.

GROMKE, C. & BLOCKEN, B. 2015. Influence of avenue-trees on air quality at the urban neighborhood scale. Part I: Quality assurance studies and turbulent Schmidt number analysis for RANS CFD simulations. *Environmental Pollution,* 196**,** 214-223.

GROSS, A. & STOCKWELL, W. R. 2003. Comparison of the EMEP, RADM2 and RACM mechanisms. *Journal of Atmospheric Chemistry,* 44**,** 151-170.

HASSAN, A. A. & CROWTHER, J. M. 1998. Modelling of fluid flow and pollutant dispersion in a street canyon. *Environmental Monitoring and Assessment,* 52**,** 281-297.

HEARD, A. C., PILLING, M. J. & TOMLIN, A. S. 1998. Mechanism reduction techniques applied to tropospheric chemistry. *Atmospheric Environment,* 32**,** 1059-1073.

HOYDYSH, W. G. & DABBERDT, W. F. 1988. KINEMATICS AND DISPERSION CHARACTERISTICS OF FLOWS IN ASYMMETRIC STREET CANYONS. *Atmospheric Environment,* 22**,** 2677-2689.

HUANG, H., AKUTSU, Y., ARAI, M. & TAMURA, M. 2000. A two-dimensional air quality model in an urban street canyon: evaluation and sensitivity analysis. *Atmospheric Environment,* 34**,** 689-698.

ITO, A., SILLMAN, S. & PENNER, J. E. 2007. Effects of additional nonmethane volatile organic compounds, organic nitrates, and direct emissions of oxygenated organic species on global tropospheric chemistry. *Journal of Geophysical Research-Atmospheres,* 112**,** doi:10.1029/2005JD006556.

JENKIN, M. E., SAUNDERS, S. M., DERWENT, R. G. & PILLING, M. J. 1997. Construction and application of a master chemical mechanism (MCM) for modelling tropospheric chemistry. *Abstracts of Papers of the American Chemical Society,* 214**,** 116-COLL.

JENKIN, M. E., SAUNDERS, S. M., DERWENT, R. G. & PILLING, M. J. 2002. Development of a reduced speciated VOC degradation mechanism for use in ozone models. *Atmospheric Environment,* 36**,** 4725-4734.

JENKIN, M. E., SAUNDERS, S. M., WAGNER, V. & PILLING, M. J. 2003. Protocol for the development of the Master Chemical Mechanism, MCM v3 (Part B): tropospheric degradation of aromatic volatile organic compounds. *Atmospheric Chemistry and Physics,* 3**,** 181-193.

JENKIN, M. E., WATSON, L. A., UTEMBE, S. R. & SHALLCROSS, D. E. 2008. A Common Representative Intermediates (CRI) mechanism for VOC degradation. Part 1: Gas phase mechanism development. *Atmospheric Environment,* 42**,** 7185-7195.

JENKIN, M. E., WYCHE, K. P., EVANS, C. J., CARR, T., MONKS, P. S., ALFARRA, M. R., BARLEY, M. H., MCFIGGANS, G. B., YOUNG, J. C. & RICKARD, A. R. 2012. Development and chamber evaluation of the MCM v3.2 degradation scheme for beta-caryophyllene. *Atmospheric Chemistry and Physics,* 12**,** 5275-5308.

JEONG, S. J. & ANDREWS, M. J. 2002. Application of the kappa-epsilon turbulence model to the high Reynolds number skimming flow field of an urban street canyon. *Atmospheric Environment,* 36**,** 1137-1145.

JIMENEZ, P., BALDASANO, J. M. & DABDUB, D. 2003. Comparison of photochemical mechanisms for air quality modeling. *Atmospheric Environment,* 37**,** 4179-4194.

JOHNSON, W. B., LUDWIG, F. L., DABBERDT, W. F. & ALLEN, R. J. 1973. URBAN DIFFUSION SIMULATION MODEL FOR CARBON-MONOXIDE. *Journal of the Air Pollution Control Association,* 23**,** 490-498.

KAKOSIMOS, K. E., HERTEL, O., KETZEL, M. & BERKOWICZ, R. 2010. Operational Street Pollution Model (OSPM) - a review of performed application and validation studies, and future prospects. *Environmental Chemistry,* 7**,** 485-503.

KANDA, M., MORIWAKI, R. & KASAMATSU, F. 2004. Large-eddy simulation of turbulent organized structures within and above explicitly resolved cube arrays. *Boundary-Layer Meteorology,* 112**,** 343-368.

KANG, Y.-S., BAIK, J.-J. & KIM, J.-J. 2008. Further studies of flow and reactive pollutant dispersion in a street canyon with bottom heating. *Atmospheric Environment,* 42**,** 4964-4975.

KASTNER-KLEIN, P., FEDOROVICH, E. & ROTACH, M. W. 2001. A wind tunnel study of organised and turbulent air motions in urban street canyons. *Journal of Wind Engineering and Industrial Aerodynamics,* 89**,** 849-861.

KASTNER-KLEIN, P. & PLATE, E. J. 1999. Wind-tunnel study of concentration fields in street canyons. *Atmospheric Environment,* 33**,** 3973-3979.

KIKUMOTO, H. & OOKA, R. 2012. A numerical study of air pollutant dispersion with bimolecular chemical reactions in an urban street canyon using large-eddy simulation. *Atmospheric Environment,* 54**,** 456-464.

KIM, J. J. & BAIK, J. J. 2001. Urban street-canyon flows with bottom heating. *Atmospheric Environment,* 35**,** 3395-3404.

KIM, J. J. & BAIK, J. J. 2003. Effects of inflow turbulence intensity on flow and pollutant dispersion in an urban street canyon. *Journal of Wind Engineering and Industrial Aerodynamics,* 91**,** 309-329.

KIM, J. J. & BAIK, J. J. 2004. A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k-epsilon turbulence model. *Atmospheric Environment,* 38**,** 3039-3048.

KIM, M. J., PARK, R. J. & KIM, J. J. 2012. Urban air quality modeling with full O-3-NOx-VOC chemistry: Implications for O-3 and PM air quality in a street canyon. *Atmospheric Environment,* 47**,** 330-340.

KOUTSOURAKIS, N., BARTZIS, J. G. & MARKATOS, N. C. 2012. Evaluation of Reynolds stress, k-epsilon and RNG k-epsilon turbulence models in street canyon flows using various experimental datasets. *Environmental Fluid Mechanics,* 12**,** 379-403.

KOVAR-PANSKUS, A., LOUKA, P., SINI, J. F., SAVORY, E., CZECH, M., ABDELQARI, A., MESTAYER, P. G. & TOY, N. 2002. *Influence of geometry on the mean flow within urban street canyons - A comparison of wind tunnel experiments and numerical simulations.*

KUMAR, P., FENNELL, P. & BRITTER, R. 2008. Effect of wind direction and speed on the dispersion of nucleation and accumulation mode particles in an urban street canyon. *Science of the Total Environment,* 402**,** 82-94.

KWAK, K.-H., BAIK, J.-J., RYU, Y.-H. & LEE, S.-H. 2015. Urban air quality simulation in a high-rise building area using a CFD model coupled with mesoscale meteorological and chemistry-transport models. *Atmospheric Environment,* 100**,** 167-177.

KWAK, K. H. & BAIK, J. J. 2012. A CFD modeling study of the impacts of NOx and VOC emissions on reactive pollutant dispersion in and above a street canyon. *Atmospheric Environment,* 46**,** 71-80.

KWAK, K. H. & BAIK, J. J. 2014. Diurnal variation of NOx and ozone exchange between a street canyon and the overlying air. *Atmospheric Environment,* 86**,** 120-128.

KWAK, K. H., BAIK, J. J. & LEE, K. Y. 2013. Dispersion and photochemical evolution of reactive pollutants in street canyons. *Atmospheric Environment,* 70**,** 98-107.

LI, X.-X., LEUNG, D. Y. C., LIU, C.-H. & LAM, K. M. 2008a. Physical modeling of flow field inside urban street canyons. *Journal of Applied Meteorology and Climatology,* 47**,** 2058-2067.

LI, X.-X., LIU, C.-H. & LEUNG, D. Y. C. 2008b. Large-eddy simulation of flow and pollutant dispersion in high-aspect-ratio urban street canyons with wall model. *Boundary-Layer Meteorology,* 129**,** 249-268.

LI, X. X., BRITTER, R. E., NORFORD, L. K., KOH, T. Y. & ENTEKHABI, D. 2012. Flow and Pollutant Transport in Urban Street Canyons of Different Aspect Ratios with Ground Heating: Large-Eddy Simulation. *Boundary-Layer Meteorology,* 142**,** 289-304.

LI, X. X., LEUNG, D. Y. C., LIU, C. H. & LAM, K. M. 2008c. Physical modeling of flow field inside urban street canyons. *Journal of Applied Meteorology and Climatology,* 47**,** 2058-2067.

LI, X. X., LIU, C. H. & LEUNG, D. Y. C. 2009. Numerical investigation of pollutant transport characteristics inside deep urban street canyons. *Atmospheric Environment,* 43**,** 2410-2418.

LI, X. X., LIU, C. H., LEUNG, D. Y. C. & LAM, K. M. 2006. Recent progress in CFD modelling of wind field and pollutant transport in street canyons. *Atmospheric Environment,* 40**,** 5640-5658.

LIU, C.-H., CHENG, W. C., LEUNG, T. C. Y. & LEUNG, D. Y. C. 2011. On the mechanism of air pollutant re-entrainment in two-dimensional idealized street canyons. *Atmospheric Environment,* 45**,** 4763-4769.

LIU, C.-H. & LEUNG, D. Y. C. 2008. Numerical study on the ozone formation inside street canyons using a chemistry box model. *Journal of Environmental Sciences-China,* 20**,** 832-837.

LIU, C. H. & BARTH, M. C. 2002. Large-eddy simulation of flow and scalar transport in a modeled street canyon. *Journal of Applied Meteorology,* 41**,** 660-673.

LIU, C. H., BARTH, M. C. & LEUNG, D. Y. C. 2004. Large-eddy simulation of flow and pollutant transport in street canyons of different building-height-to-street-width ratios. *Journal of Applied Meteorology,* 43**,** 1410-1424.

LIU, C. H., LEUNG, D. Y. C. & BARTH, M. C. 2005. On the prediction of air and pollutant exchange rates in street canyons of different aspect ratios using large-eddy simulation. *Atmospheric Environment,* 39**,** 1567-1574.

LOUKA, P., BELCHER, S. E. & HARRISON, R. G. 2000. Coupling between air flow in streets and the well-developed boundary layer aloft. *Atmospheric Environment,* 34**,** 2613-2621.

LOVAS, T., MASTORAKOS, E. & GOUSSIS, D. A. 2006. Reduction of the RACM scheme using computational singular perturbation analysis. *Journal of Geophysical Research-Atmospheres,* 111**,** doi:10.1029/2005JD006743.

MADALOZZO, D. M. S., BRAUN, A. L., AWRUCH, A. M. & MORSCH, I. B. 2014. Numerical simulation of pollutant dispersion in street canyons: Geometric and thermal effects. *Applied Mathematical Modelling,* 38**,** 5883-5909.

MAKAR, P. A. & POLAVARAPU, S. M. 1997. Analytic solutions for gas-phase chemical mechanism compression. *Atmospheric Environment,* 31**,** 1025-1039.

MAUERSBERGER, G. 2005. ISSA (iterative screening and structure analysis) - a new reduction method and its application to the tropospheric cloud chemical mechanism RACM/CAPRAM2.4. *Atmospheric Environment,* 39**,** 4341-4350.

MCHUGH, C. A., CARRUTHERS, D. J. & EDMUNDS, H. A. 1997. ADMS-Urban: an air quality management system for traffic, domestic and industrial pollution. *International Journal of Environment and Pollution,* 8**,** 666-674.

MCNABOLA, A., BRODERICK, B. M. & GILL, L. W. 2009. A numerical investigation of the impact of low boundary walls on pedestrian exposure to air pollutants in urban street canyons. *Science of the Total Environment,* 407**,** 760-769.

MEMON, R. A., LEUNG, D. Y. C. & LIU, C.-H. 2010. Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons. *Building and Environment,* 45**,** 176-188.

MERONEY, R. N., PAVAGEAU, M., RAFAILIDIS, S. & SCHATZMANN, M. 1996. Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. *Journal of Wind Engineering and Industrial Aerodynamics,* 62**,** 37-56.

MICHIOKA, T. & SATO, A. 2012. Effect of Incoming Turbulent Structure on Pollutant Removal from Two-Dimensional Street Canyon. *Boundary-Layer Meteorology,* 145**,** 469-484.

MICHIOKA, T., SATO, A., TAKIMOTO, H. & KANDA, M. 2011. Large-Eddy Simulation for the Mechanism of Pollutant Removal from a Two-Dimensional Street Canyon. *Boundary-Layer Meteorology,* 138**,** 195-213.

MUNIR, S., CHEN, H. & ROPKINS, K. 2013. Quantifying temporal trends in ground level ozone concentration in the UK. *Science of the Total Environment,* 458**,** 217-227.

MURENA, F. 2012. Monitoring and modelling carbon monoxide concentrations in a deep street canyon: application of a two-box model. *Atmospheric Pollution Research,* 3**,** 311-316.

MURENA, F., DI BENEDETTO, A., D'ONOFRIO, M. & VITIELLO, G. 2011. Mass Transfer Velocity and Momentum Vertical Exchange in Simulated Deep Street Canyons. *Boundary-Layer Meteorology,* 140**,** 125-142.

MURENA, F. & FAVALE, G. 2007. Continuous monitoring of carbon monoxide in a deep street canyon. *Atmospheric Environment,* 41**,** 2620-2629.

MURENA, F., FAVALE, G., VARDOULAKIS, S. & SOLAZZO, E. 2009. Modelling dispersion of traffic pollution in a deep street canyon: Application of CFD and operational models. *Atmospheric Environment,* 43**,** 2303-2311.

MURENA, F., GAROFALO, N. & FAVALE, G. 2008. Monitoring CO concentration at leeward and windward sides in a deep street canyon. *Atmospheric Environment,* 42**,** 8204-8210.

NAEI 2003. UK fleet composition projections. *URL: http://naei.defra.gov.uk/data/ef-transport*.

NAZRIDOUST, K. & AHMADI, G. 2006. Airflow and pollutant transport in street canyons. *Journal of Wind Engineering and Industrial Aerodynamics,* 94**,** 491-522.

NEOPHYTOU, M. K., GOUSSIS, D. A., VAN LOON, M. & MASTORAKOS, E. 2004. Reduced chemical mechanisms for atmospheric pollution using Computational Singular Perturbation analysis. *Atmospheric Environment,* 38**,** 3661-3673.

O'NEILL, J. J., CAI, X. M. & KINNERSLEY, R. 2015. Improvement of a stochastic backscatter model and application to large-eddy simulation of street canyon flow *Quarterly Journal of the Royal Meteorological Society,* Accepted.

OKE, T. R. 1987. Boundary Layer Climates. *second ed,* Methuen**,** London.

PARK, S.-J., KIM, J.-J., KIM, M. J., PARK, R. J. & CHEONG, H.-B. 2015. Characteristics of flow and reactive pollutant dispersion in urban street canyons. *Boundary-Layer Meteorology,* 108**,** 20-31.

PINHO, P. G., PIO, C. A., CARTER, W. P. L. & JENKIN, M. E. 2007. Evaluation of alpha- and beta-pinene degradation in the detailed tropospheric chemistry mechanism, MCM v3.1, using environmental chamber data. *Journal of Atmospheric Chemistry,* 57**,** 171-202.

PÖSCHL, U., VON KUHLMANN, R., POISSON, N. & CRUTZEN, P. J. 2000. Development and intercomparison of condensed isoprene oxidation mechanisms for global atmospheric modeling. *Journal of Atmospheric Chemistry,* 37**,** 29-52.

SAHM, P., LOUKA, P., KETZEL, M., GUILLOTEAU, E. & SINI, J. F. 2002. *Intercomparison of numerical urban dispersion models - Part I: Street canyon and single building configurations*.

SALIM, S. M., BUCCOLIERI, R., CHAN, A. & DI SABATINO, S. 2011a. Numerical simulation of atmospheric pollutant dispersion in an urban street canyon: Comparison between RANS and LES. *Journal of Wind Engineering and Industrial Aerodynamics,* 99**,** 103-113.

SALIM, S. M., CHEAH, S. C. & CHAN, A. 2011b. Numerical simulation of dispersion in urban street canyons with avenue-like tree plantings: Comparison between RANS and LES. *Building and Environment,* 46**,** 1735-1746.

SALIZZONI, P., MARRO, M., SOULHAC, L., GROSJEAN, N. & PERKINS, R. J. 2011. Turbulent Transfer Between Street Canyons and the Overlying Atmospheric Boundary Layer. *Boundary-Layer Meteorology,* 141**,** 393-414.

SALIZZONI, P., SOULHAC, L. & MEJEAN, P. 2009. Street canyon ventilation and atmospheric turbulence. *Atmospheric Environment,* 43**,** 5056-5067.

SANTIAGO, J. L., DEJOAN, A., MARTILLI, A., MARTIN, F. & PINELLI, A. 2010. Comparison Between Large-Eddy Simulation and Reynolds-Averaged Navier-Stokes Computations for

the MUST Field Experiment. Part I: Study of the Flow for an Incident Wind Directed Perpendicularly to the Front Array of Containers. *Boundary-Layer Meteorology,* 135**,** 109-132.

SAUNDERS, S. M., JENKIN, M. E., DERWENT, R. G. & PILLING, M. J. 2003. Protocol for the development of the Master Chemical Mechanism, MCM v3 (Part A): tropospheric degradation of non-aromatic volatile organic compounds. *Atmospheric Chemistry and Physics,* 3**,** 161-180.

SCHUMANN, U. 1975. SUBGRID SCALE MODEL FOR FINITE-DIFFERENCE SIMULATIONS OF TURBULENT FLOWS IN PLANE CHANNELS AND ANNULI. *Journal of Computational Physics,* 18**,** 376-404.

SEINFELD, J. H. & PANDIS, S. N. 1998. Atmospheric chemistry and physics: from air pollution to climate change. *Wiley***,** New York.

SINI, J. F., ANQUETIN, S. & MESTAYER, P. G. 1996. Pollutant dispersion and thermal effects in urban street canyons. *Atmospheric Environment,* 30**,** 2659-2677.

SMAGORINSKY, J. 1963. General circulation experiments with the primitive equations. *Monthly Weather Review,* 91**,** 99-164.

SOLAZZO, E. & BRITTER, R. E. 2007. Transfer processes in a simulated urban street canyon. *Boundary-Layer Meteorology,* 124**,** 43-60.

SOLAZZO, E., CAI, X. & VARDOULAKIS, S. 2008. Modelling wind flow and vehicle-induced turbulence in urban streets. *Atmospheric Environment,* 42**,** 4918-4931.

SOLAZZO, E., VARDOULAKIS, S. & CAI, X. 2011. A novel methodology for interpreting air quality measurements from urban streets using CFD modelling. *Atmospheric Environment,* 45**,** 5230-5239.

SOULHAC, L., PERKINS, R. J. & SALIZZONI, P. 2008. Flow in a street canyon for any external wind direction. *Boundary-Layer Meteorology,* 126**,** 365-388.

SOULHAC, L. & SALIZZONI, P. 2010. Dispersion in a street canyon for a wind direction parallel to the street axis. *Journal of Wind Engineering and Industrial Aerodynamics,* 98**,** 903-910.

STOCKWELL, W. R., KIRCHNER, F., KUHN, M. & SEEFELD, S. 1997. A new mechanism for regional atmospheric chemistry modeling. *Journal of Geophysical Research-Atmospheres,* 102**,** 25847-25879.

STOCKWELL, W. R., LAWSON, C. V., SAUNDERS, E. & GOLIFF, W. S. 2012. A Review of Tropospheric Atmospheric Chemistry and Gas-Phase Chemical Mechanisms for Air Quality Modeling. *Atmosphere,* 3**,** 1-32.

STOCKWELL, W. R., MIDDLETON, P., CHANG, J. S. & TANG, X. 1990. The second generation regional Acid Deposition Model chemical mechanism for regional air quality modeling. *J. Geophys. Res.,* 95**,** 16343-16367.

TARABORRELLI, D., LAWRENCE, M. G., BUTLER, T. M., SANDER, R. & LELIEVELD, J. 2009. Mainz Isoprene Mechanism 2 (MIM2): an isoprene oxidation mechanism for regional and global atmospheric modelling. *Atmospheric Chemistry and Physics,* 9**,** 2751-2777.

TIAN, S., LIANG, Z.-Y. & ZHANG, G.-B. 2009. Preliminary plan of numerical simulations of three dimensional flow-field in street canyons. *Icicta: 2009 Second International Conference on Intelligent Computation Technology and Automation, Vol Ii, Proceedings.*

TOMINAGA, Y. & STATHOPOULOS, T. 2010. Numerical simulation of dispersion around an isolated cubic building: Model evaluation of RANS and LES. *Building and Environment,* 45**,** 2231-2239.

TOMINAGA, Y. & STATHOPOULOS, T. 2011. CFD modeling of pollution dispersion in a street canyon: Comparison between LES and RANS. *Journal of Wind Engineering and Industrial Aerodynamics,* 99**,** 340-348.

TONG, N. Y. O. & LEUNG, D. Y. C. 2012. Effects of building aspect ratio, diurnal heating scenario, and wind speed on reactive pollutant dispersion in urban street canyons. *Journal of Environmental Sciences-China,* 24**,** 2091-2103.

TSAI, M. Y. & CHEN, K. S. 2004. Measurements and three-dimensional modeling of air pollutant dispersion in an Urban Street Canyon. *Atmospheric Environment,* 38**,** 5911-5924.

UEHARA, K., MURAKAMI, S., OIKAWA, S. & WAKAMATSU, S. 2000. Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons. *Atmospheric Environment,* 34**,** 1553-1562.

VARDOULAKIS, S., FISHER, B. E. A., PERICLEOUS, K. & GONZALEZ-FLESCA, N. 2003. Modelling air quality in street canyons: a review. *Atmospheric Environment,* 37**,** 155-182.

VARDOULAKIS, S., VALIANTIS, M., MILNER, J. & APSIMON, H. 2007. Operational air pollution modelling in the UK - Street canyon applications and challenges. *Atmospheric Environment,* 41**,** 4622-4637.

VERWER, J. G. & SIMPSON, D. 1995. EXPLICIT METHODS FOR STIFF ODES FROM ATMOSPHERIC CHEMISTRY. *Applied Numerical Mathematics,* 18**,** 413-430.

WALTON, A. & CHENG, A. Y. S. 2002. Large-eddy simulation of pollution dispersion in an urban street canyon - Part II: idealised canyon simulation. *Atmospheric Environment,* 36**,** 3615-3627.

WALTON, A., CHENG, A. Y. S. & YEUNG, W. C. 2002. Large-eddy simulation of pollution dispersion in an urban street canyon - Part I: comparison with field data. *Atmospheric Environment,* 36**,** 3601-3613.

WATSON, L. A., SHALLCROSS, D. E., UTEMBE, S. R. & JENKIN, M. E. 2008. A Common Representative Intermediates (CRI) mechanism for VOC degradation. Part 2: Gas phase mechanism reduction. *Atmospheric Environment,* 42**,** 7196-7204.

WHITEHOUSE, L. E., TOMLIN, A. S. & PILLING, M. J. 2004. Systematic reduction of complex tropospheric chemical mechanisms, Part I: sensitivity and time-scale analyses. *Atmospheric Chemistry and Physics,* 4**,** 2025-2056.

WHO 2000. Air Quality Guidelines for Europe. *WHO Regional Publications, Europen series,* No. 91**,** Second ed.

XIE, S. D., ZHANG, Y. H., LI, Q. & TANG, X. Y. 2003. Spatial distribution of traffic-related pollutant concentrations in street canyons. *Atmospheric Environment,* 37**,** 3213-3224.

XIE, X., LIU, C.-H., LEUNG, D. Y. C. & LEUNG, M. K. H. 2006. Characteristics of air exchange in a street canyon with ground heating. *Atmospheric Environment,* 40**,** 6396-6409.

XIE, X. M., HUANG, Z., WANG, J. S. & XIE, Z. 2005. The impact of solar radiation and street layout on pollutant dispersion in street canyon. *Building and Environment,* 40**,** 201-212.

XIE, X. M., WANG, J. S. & HUANG, Z. 2009. Traffic Emission Transportation in Street Canyons. *Journal of Hydrodynamics,* 21**,** 108-117.

XIE, Z. & CASTRO, I. P. 2006. LES and RANS for turbulent flow over arrays of wall-mounted obstacles. *Flow Turbulence and Combustion,* 76**,** 291-312.

YAKHOT, V. & ORSZAG, S. A. 1986. RENORMALIZATION-GROUP ANALYSIS OF TURBULENCE. *Physical Review Letters,* 57**,** 1722-1724.

YAZID, A. W. M., SIDIK, N. A. C., SALIM, S. M. & SAQR, K. M. 2014. A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies. *Simulation-Transactions of the Society for Modeling and Simulation International,* 90**,** 892-916.

ZAVERI, R. A. & PETERS, L. K. 1999. A new lumped structure photochemical mechanism for large-scale applications. *Journal of Geophysical Research-Atmospheres,* 104**,** 30387-30415.

ZHONG, J., CAI, X. & BLOSS, W. J. 2014. Modelling segregation effects of heterogeneous emissions on ozone levels in idealised urban street canyons: Using photochemical box models *Environmental Pollution,* 188**,** 132-143.

ZHONG, J., CAI, X. & BLOSS, W. J. 2015. Modelling the dispersion and transport of reactive pollutants in a deep urban street canyon: Using large-eddy simulation. *Environmental Pollution,* 200**,** 42-52.