Parameterizing Urban Canopy Layer transport in a Lagrangian Particle Dispersion Model

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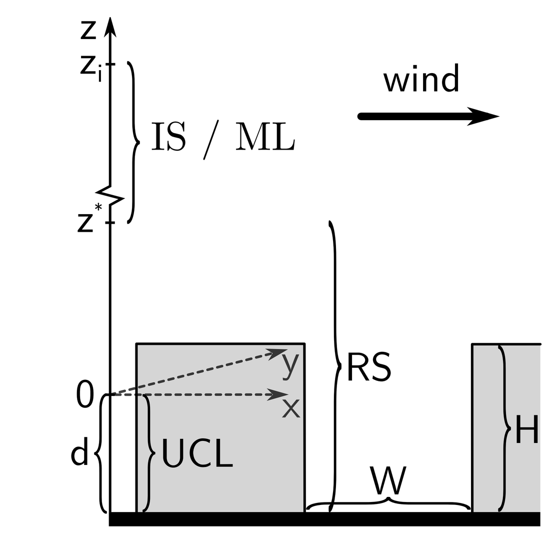
① Motivation

- Many people and pollutant sources in urban areas, hence pollutant dispersion important
- Rotach et al. (2004) propose idea to further improve their dispersion model
- Goal of this work is to implement and evaluate that idea:

Hypothesis

Including transport in street canyons improves model performance.

② Existing model



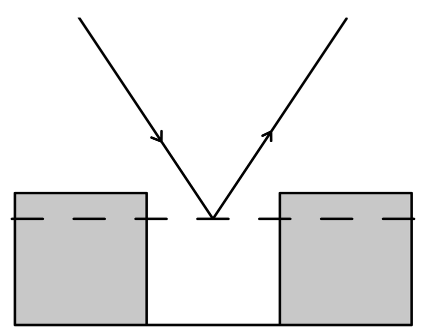
Model domain, coordinate system with zero plane displacement $\boldsymbol{d}$, building height $\boldsymbol{H}$ and width $\boldsymbol{W}$

- Rotach et al. (1996)
  - well mixed Lagrangian stochastic dispersion
  - Fokker-Planck and Langevin equation
  - 3-dimensional, but horizontally homogeneous
  - convective, neutral and stable conditions
  - mean wind always in $\boldsymbol{x}$-direction
- Rotach (2001)
  - roughness sublayer (RS) turbulence parameterization using local $\boldsymbol{u_*}$
- Uses kernel method to calculate tracer concentration after point release
- Lower boundary at zero plane displacement $\boldsymbol{d}$

③ Model evaluation method

- Model output compared to field measurements of the Basel UrBan Boundary Layer Experiment (BUBBLE)
- SF_6 tracer release and sampling along arcs in stationary conditions
- Relative Difference (RD), Normalized Mean Square Error (NMSE), Fractional Bias (FB), CORRelation coefficient (CORR) and Factor of Two (F2) to compare measured and simulated concentrations
- Blocked moment bootstrap of difference to evaluate significance

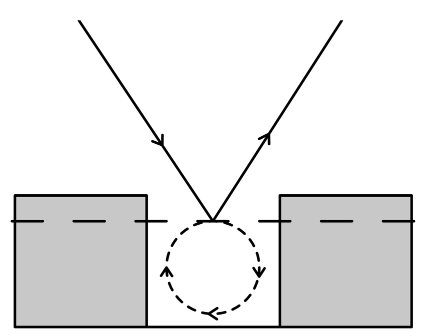
④ Old lower boundary conditions



Conceptual sketch of a particle trajectory reflected at the zero plane displacement.

Reflection

- classical approach
- particle immediately reflected
- vertical and horizontal velocity perturbation have their sign inverted
- upper boundary condition analog



As above, but particle may stay "trapped" for a while.

Residence time

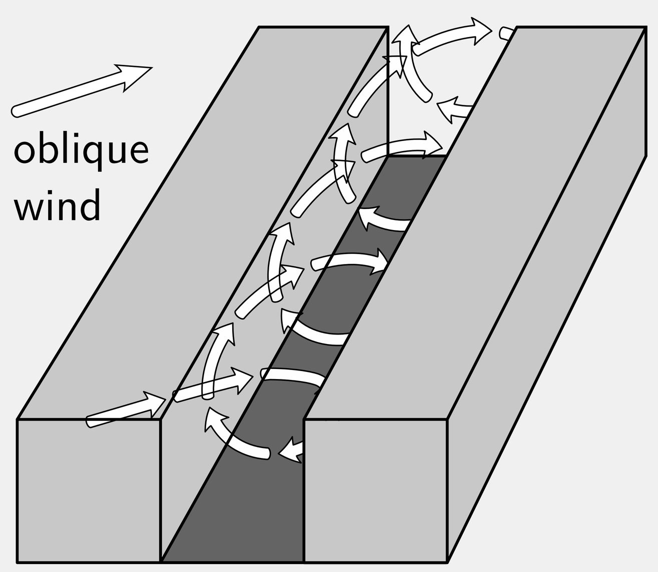
- introduced in Rotach et al. (2004)
- 33% chance of trapping, 67% reflection
- particle does not move during trapping
- stays trapped for $\tau = \frac{4H}{\overline{u}_H}$, where $\overline{u}_H$ is mean rooftop wind velocity

⑤ New lower boundary condition

Drift

- similar to residence time approach, but particles move while trapped
- movement depends on wind speed and street canyon direction
- details in Stöckl (2015)

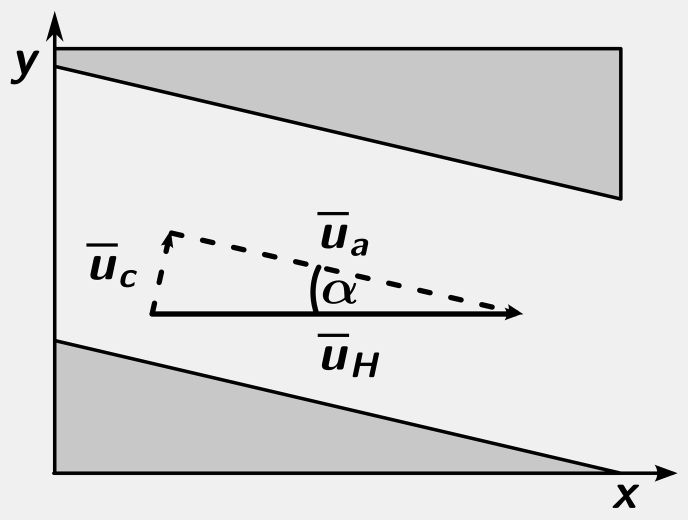
Assumptions



Simplified diagram of a corkscrew vortex in a street canyon

- skimming flow regime (H/W $\approx$ 1)
- endless street canyons without intersections
- corkscrew vortex forms if oblique incidence angle ($> 30°$) of wind on canyon and rooftop wind speed $\overline{u}_H > 1.5$ m s^{-1}
- canyon direction chosen from discrete, empirical distribution
- 50% chance of hitting canyon (geometry of Basel)
- 66% chance to penetrate shear layer at roof top level

Wind velocity decomposition



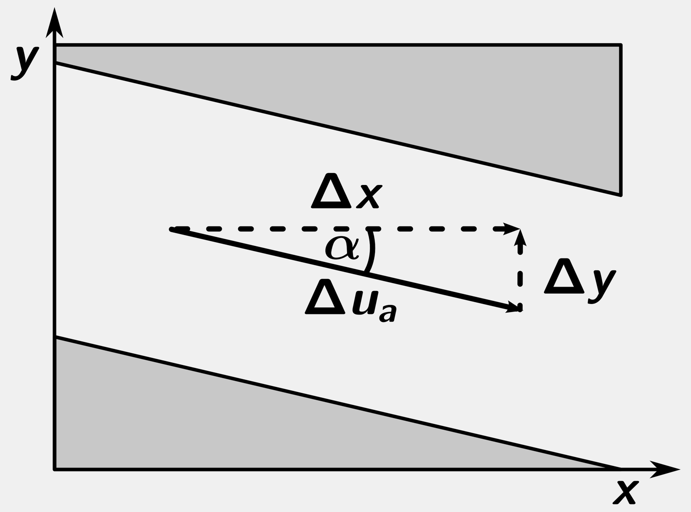
Top down view on an oblique canyon and the rooftop velocity decomposition

Decompose mean rooftop velocity into along canyon and cross canyon component:

$$\overline{u}_a = p_a \overline{u}_H \cos\alpha$$
$$\overline{u}_c = p_c \overline{u}_H \sin\alpha$$

If vortex forms: $\tau = \frac{2H}{\overline{u}_c}$, else $\tau = \frac{2d}{w}$. The factor $\boldsymbol{p_a} = \mathbf{0.8}$ is estimated from literature by averaging empirical wind speed profiles. $\boldsymbol{p_c} = \mathbf{0.4}$ is the average factor of circumferential velocity estimated from literature.

Drift calculation



As above, now the drift along the canyon is split into $\boldsymbol{x}$ and $\boldsymbol{y}$-coordinates

Randomly circulate multiple times with 66 % chance to escape by multiplying τ. Then use residence time τ and along canyon wind speed to calculate particle movement

$$\Delta u_a = \overline{u}_a \tau$$
$$\Delta x = \Delta u_a \cos\alpha$$
$$\Delta y = \Delta u_a \sin\alpha$$

This displacement is added to each trapped particle for each time step it stays trapped in the canyon.

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More details (Stöckl, 2015):

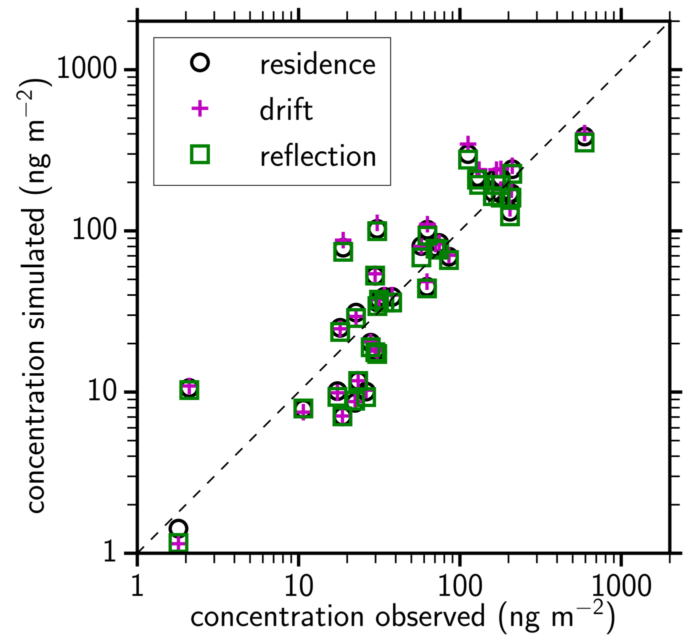
⑥ Sensitivity studies

- Canyon direction
  - tested fully parallel, fully perpendicular and empirical distribution
  - perpendicular significantly better for model performance than others
- Wind speed parameters $\boldsymbol{p_a}$ and $\boldsymbol{p_c}$
  - tested full physically reasonable range
  - $\mathbf{0.1} < \boldsymbol{p_a} < \mathbf{1.4}$ and $\mathbf{0.1} < \boldsymbol{p_c} < \mathbf{0.9}$
  - best run with $\boldsymbol{p_a} = \mathbf{0.1}$, $\boldsymbol{p_c} = \mathbf{0.9}$ (minimal movement, fastest ejection)

⑦ Results

Statistics overview, gray background is the base run, green background means significantly better (**95** %), magenta background significantly worse than base run; **bold** values are the best in each column; top half uses standard zero plane displacement $\boldsymbol{d}$, lower half uses larger $\boldsymbol{d}$ derived from long term measurements

Experiment	RD	FB	NMSE	CORR	F2
residence time	1.47	-0.12	**2.24**	**0.53**	**0.30**
drift	1.66	-0.22	2.34	**0.53**	**0.30**
reflection	**1.40**	**-0.06**	**2.24**	**0.53**	0.29
residence time, $\boldsymbol{d}_{new}$	1.17	**0.13**	**2.22**	**0.57**	0.34
drift, $\boldsymbol{d}_{new}$	1.19	**0.13**	**2.22**	**0.57**	0.34
reflection, $\boldsymbol{d}_{new}$	**1.07**	0.24	2.43	**0.57**	**0.35**



Concentration comparison: simulated by model and observed during BUBBLE.

- With old zero plane displacement $\boldsymbol{d}$: consistent with the results of the sensitivity studies: faster release better
- Not surprising: model generally overpredicts concentration (for BUBBLE) and trapping of particles increases that
- $\boldsymbol{d}_{new}$ changes behavior: now underpredicts, making bias of reflection worse.
- Need other field studies and further studies of into effect of $\boldsymbol{d}$ (also roughness length and RS height, not shown)

⑧ Summary

- New method to include street canyon effect in a Lagrangian particle dispersion model with zero plane displacement
- Decomposes roof top velocity, calculates mean in-canyon velocity and transports particles that pierce the lower model boundary
- Only valid in skimming flow regime
- Results inconclusive, further testing with other data sets needed
- Effect of zero plane displacement $\boldsymbol{d}$ larger than effect of boundary condition

Conclusion

Transport in street canyons worse or inconclusive, depending on value of zero plane displacement, further studies needed.

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