National Institute for Public Health
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Knowledge brief

Simulation of dispersion in a street canyon using the DALES model

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Summary

Accurate assessment of air quality in urban environments, important for the health of many people, can be challenging. A relatively new development in the assessment is the use of numerical Large-Eddy Simulations. In the project discussed here, the Dutch Atmospheric Large-Eddy Simulation (DALES) model is used to calculate the concentrations due to traffic in street canyons. The DALES model can simulate the concentration at a high temporal and spatial resolution and was successfully used by us to model the flow and concentrations in a street canyon. The results of the calculations are quite similar to measurements found in literature. Some differences are observed and discussed in our analyses.

Introduction

Air quality in urban environments directly affects the health of a large number of people. Accurate assessment is therefore important. Whereas most air quality models can provide sufficiently accurate average concentrations at street locations, the need for more detailed assessment may arise in urban areas, i.e. more complex combinations of buildings and streets. Wind-tunnel measurements are often used to assess air quality in such complex urban environments. These measurements are often expensive and time-consuming. A relatively new development in dispersion modelling is the use of numerical Large-Eddy Simulations (LES). With these simulations, it is possible to focus in more detail on areas with high concentrations and asses the air quality at a high spatial and temporal resolution, i.e. meters and seconds. In this project, the concentration in a double street canyon is studied using the Dutch Atmospheric Large-Eddy Simulation (DALES) model. The goal of this project is to investigate if the DALES model can sufficiently simulate dispersion in an urban environment. The DALES simulations were performed for a number of street configurations that are quite common in the city centers of large Dutch cities. As Large-Eddy Simulations are complex and time-consuming, a limited number of schematic situations were studied.

DALES model

DALES solves the equation of motion, plus conservation of mass and energy, for atmospheric flows, on a 3D computational grid. LES simulations are performed at a high spatial resolution (i.e. 1-50 meters), in order to also resolve the turbulent motions in these flows: the large eddies are explicitly solved at the grid itself, whereas the turbulence on the sub-grid level is parameterized. Tracers can be included in these simulations, such that one is able to calculate simultaneously the transport and dispersion of, for example, air pollutants in urban environments. In this project the concentration of a passive tracer in a double street canyon configuration is studied with DALES: these simulations yield concentration maps on a high spatial and temporal resolution. In an urban environment concentration maps on a high spatial and temporal resolution are very useful, because the concentration varies a lot in space and time.

Case description

The domain consists of a numerical grid of 80 x 64 x 100 cells and the extent of the entire domain is 232.5 m x 186 m x 200 m. So, each cell has a size of about 2.91 m x 2.91 m x 2 m. An overview of the set-up is shown in Figure 1. The wind direction was set perpendicular to the street canyon. The emission sources are placed in the middle of the street canyon along the length of the building. The emission sources are placed at every second cell, so there is a distance of 5.82 m between the emission sources. 16 emission sources are placed in each street canyon.

The input is based on the case for a neutral atmospheric boundary layer. The initial potential temperature is 290 K for every height level and the turbulent kinetic energy is set to 1 m^2/s^2. The wind has a periodic boundary condition, but the concentration is forced to zero at the edges of the domain. There is no heat flux from the buildings in this simulation.

Due to this periodic boundary condition it is important to make sure that the domain is long enough downwind of the last building. Otherwise, the first building is in the cavity zone of the last building.

Because of the periodic boundary condition of the wind, the wind speed keeps decreasing over time due to friction with the street canyon. To counter this effect a nudging of the wind profile is applied every 30 minutes of the simulation. This wind profile is given for every height level and the entire slab is nudged to this value. The West-East wind speed is equal to 0.8 m/s at a height of 1 meter and increases with height. From about a height of 35 meters the West-East wind speed is close to 7 m/s for all height levels.

First, the simulation is performed for 3 hours to spin up, to develop a numerically stable flow field. Then a warm start is performed with the spin up run and the tracers are emitted for 2 hours. The last hour of this final simulation is used for the results.

Several variations of this set-up are studied. The height of the buildings was varied as well as the width of the street canyon and the horizontal size of the grid cell. The cases studied are shown in Table 1.

Most of the simulations were performed on 4 cores of a virtual Linux machine. A spin up run with a domain of 80x64x100 cells took about 25,5 hours to complete and the warm start with 32 emission sources took 19,7 hours to complete.

Figure 1 Overview of the set-up with two street canyons. The buildings are shown in blue. The wind direction is perpendicular to the street canyons. The point sources are located at the middle of the street canyon, shown by the dotted line, at a height of 1 m.

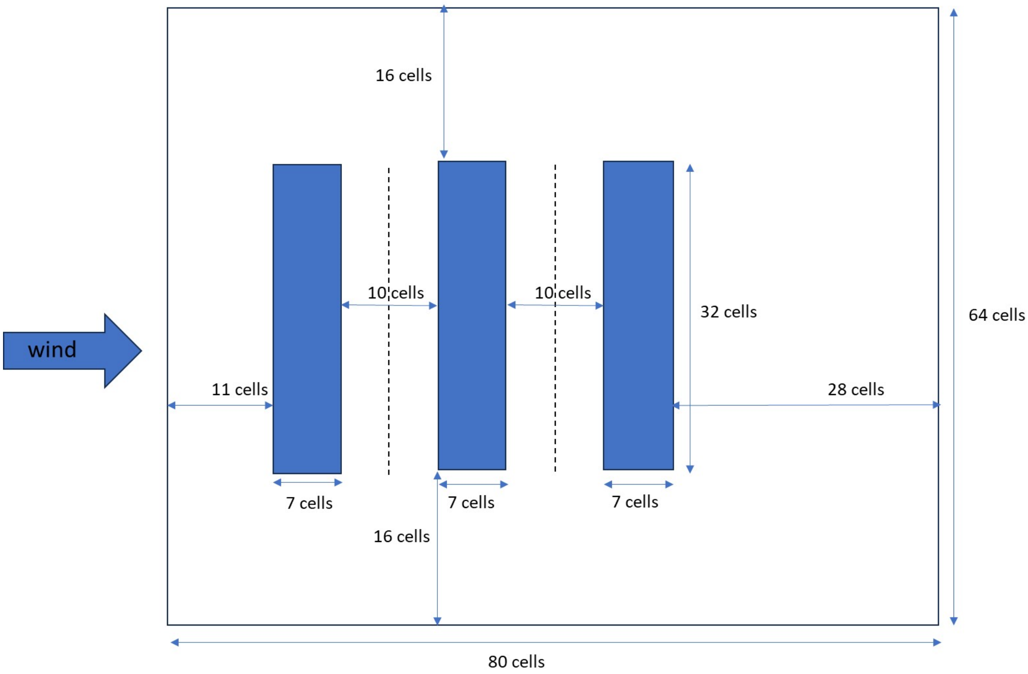


Table 1 The cases that were studied. The building height, street canyon width and cell size were varied.

Case	Cell size	Building height	Street canyon width
Building height 8 m	2.91x2.91x2 m	8 m	29.1 m
Building height 14 m "Standard case"	2.91x2.91x2 m	14 m	29.1 m
Building height 20 m	2.91x2.91x2 m	20 m	29.1 m
Building height 8-20-8 m	2.91x2.91x2 m	8,20, 8 m	29.1 m
Narrower street canyons I	2.91x2.91x2 m	14 m	20.3 m
Narrower Street canyons II	2.91x2.91x2 m	20 m	20.3 m
Higher resolution	1.45x1.45x2 m	14 m	29.1 m

In the book Urban climates from Oke et al. three flow regimes are distinguished. The isolated roughness flow, the wake interference flow and the skimming flow, as shown in Figure 2 (Oke et al., 2017). The flow regime depends both on the ratio between the building height (H) and the width of the street canyon (W) and the ratio between those two (H/W).
In Figure 3 a fog visualization from a wind tunnel experiment is shown (Llaguno-Munitxa et al., 2017). The mean flow is from left to right, but the flow in the street canyon is highly dependent on the type of roof of the buildings. In the simulations done for this project all buildings have a flat roof.

Figure 2 Three types of flow regimes for flow over building arrays (Oke et al., 2017)

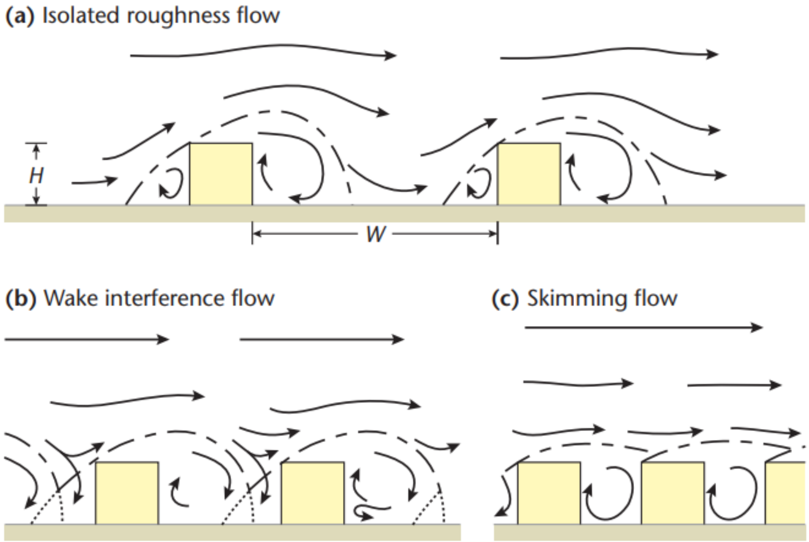


Figure 3 Fog visualizations for a flat roof, pitched roof and round roof (left to right). The mean flow is from left to right (Llaguno-Munitxa et al., 2017).

Results

Double street canyon with equal building height

The simulation for a double street canyon with a width of 29.1 meter is performed for three different building heights. A building height of 8 meter, 14 meter and 20 meter. In Figure 4 the time-averaged concentration and wind speed and direction over the last hour of the simulation at a height of 3 meter is shown for the simulation with a building height of 14 meter. In Figure 5**.** the vertical cross section of the same variables of the same simulation is shown. Here, the concentration and wind speed and direction are averaged along the length of the building. This wind direction in this cross section looks very similar to the skimming flow in Figure 2 and the flow for a flat roof shown in Figure 3, as was expected.

Figure 4 The top view of the two street canyons with a building height of 14 meters. The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and wind velocity at a height of 3 meters is shown, both are averaged over the last hour of the simulation.

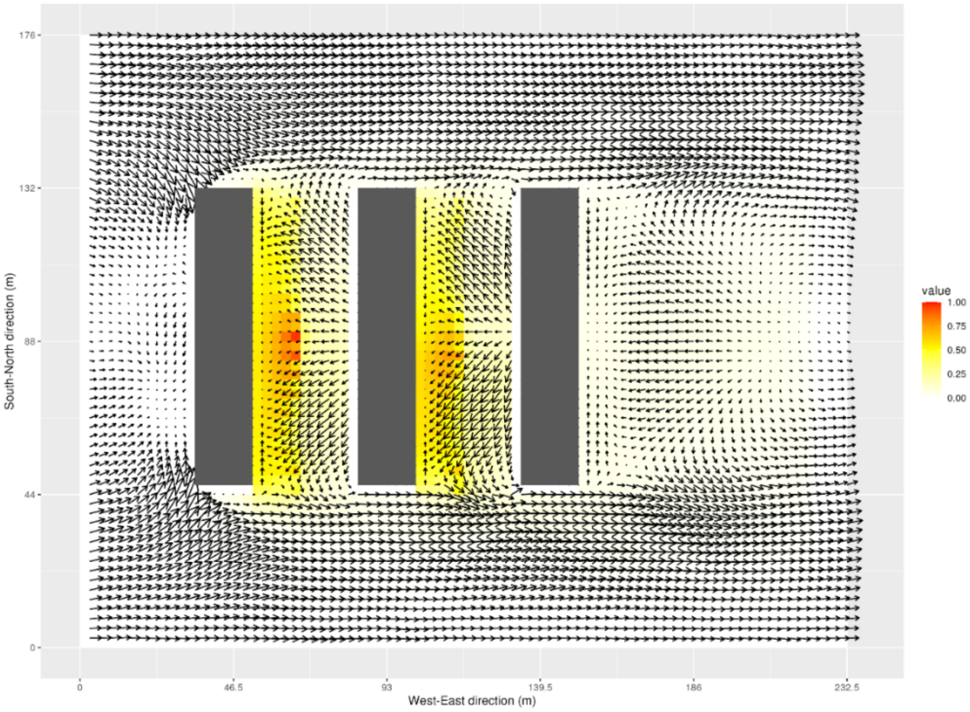
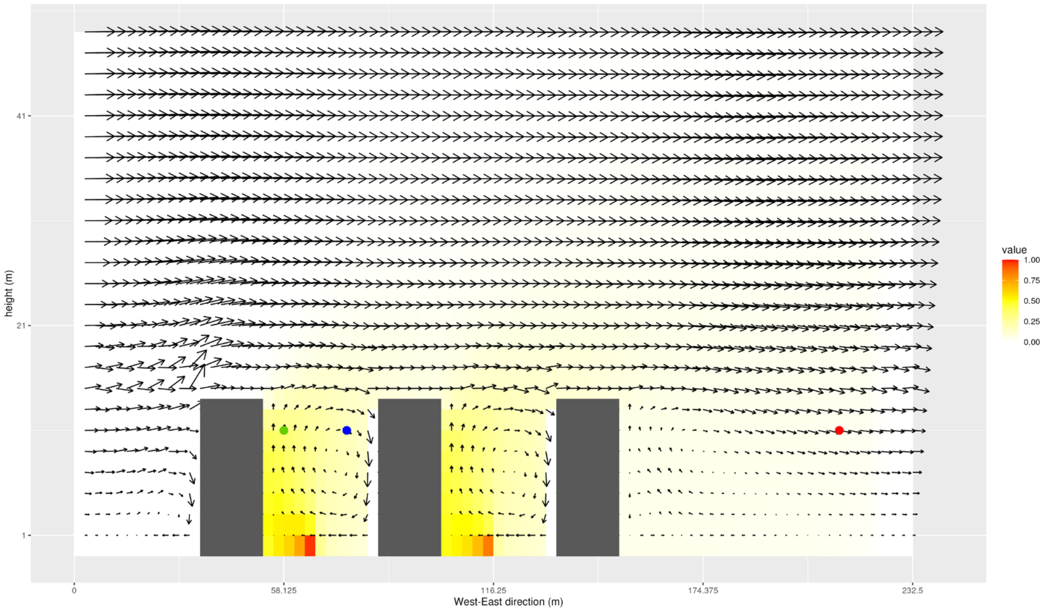


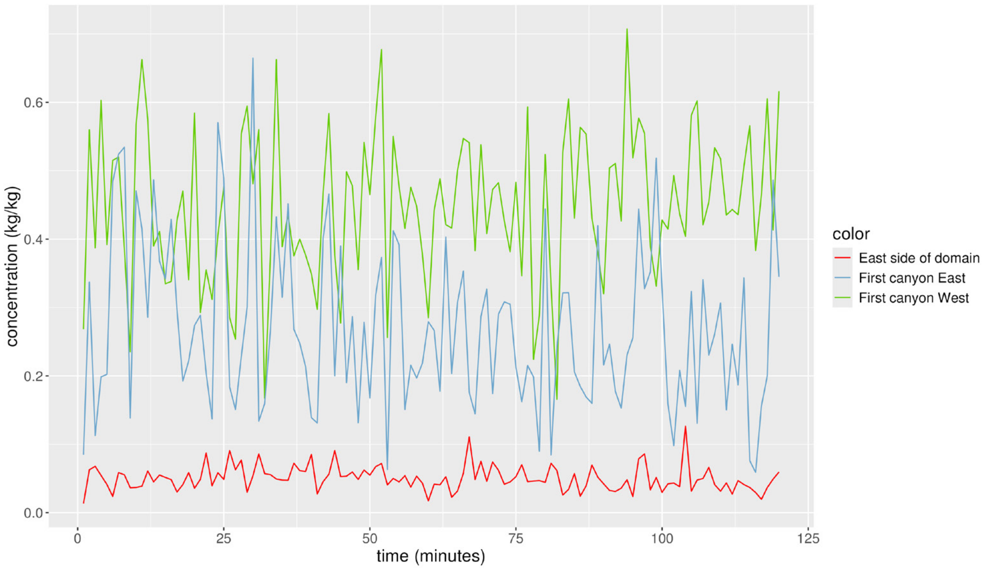
Figure 5 The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and the wind speed are averaged along the length of the building and are averaged over time for the last hour of the simulation. The colored dots show the location at which the concentration over time is sampled.



The results for the simulations with a building height of 8 meter and 20 meter look similar. However, the concentration inside the street canyon is highest for a building height of 8 meter and lowest for a building height of 20 meter. This is opposite to what is stated in the book from Oke et al. (2017). For a higher H/W ratio the air in the street canyon mixes less with the atmosphere above and therefore the concentration in the canyon remains higher. This is something that would be interesting to investigate further in future research.
It might be possible that there is very little mixing of the air in the street canyon with the air outside the street canyon. The vortex is higher when the building height is higher, resulting in more mixing and dispersion inside the street canyon for a higher building. Another possibility is that there is a lot of ventilation at the sides of the street canyon. The area where clean air from outside the street canyon can mix with the air inside the street canyon is larger when the building height is larger.

There is clearly a large difference between the concentration on the East side and the West side of the canyon at a height of 3 meter. In Figure 6, the concentration over time is shown for 3 different locations at a height of 11 meter (see dots with corresponding colors in Figure 5**.**).

Figure 6 The concentration over time at a height of 11 meter at the East side of the domain, the West side of the first canyon and the East side of the first canyon.



In Figure 7 and Figure 8, the horizontal and vertical cross section of the concentration and wind direction are shown for 2 time snapshots. The flow is very turbulent. Therefore the plumes fluctuate and the location of the highest concentration varies a lot over time.

Figure 7 The top view of the two street canyons with a building height of 14 meters. The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and wind velocity at a height of 3 meters are shown for two snapshots.

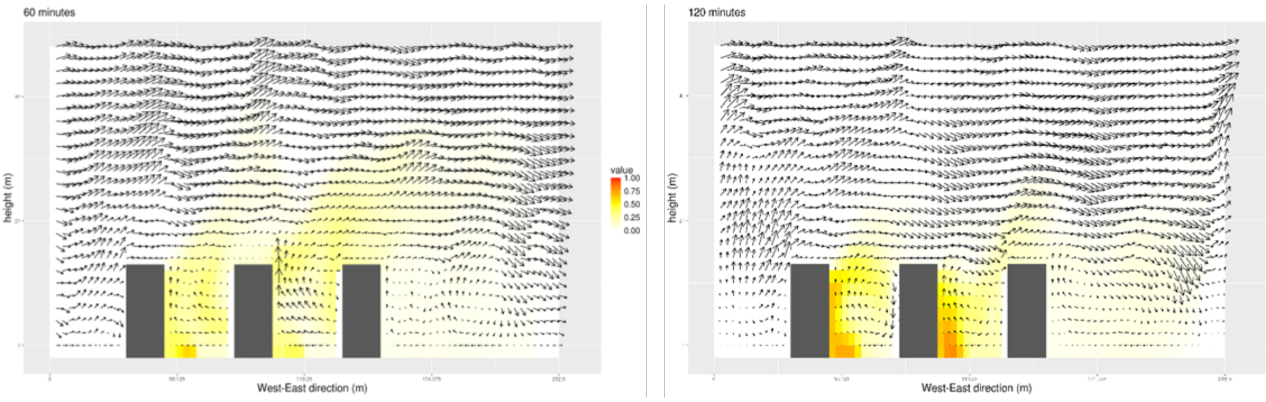


Figure 8 The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and the wind speed is shown for the middle of the domain in the South-North direction for two snapshots.

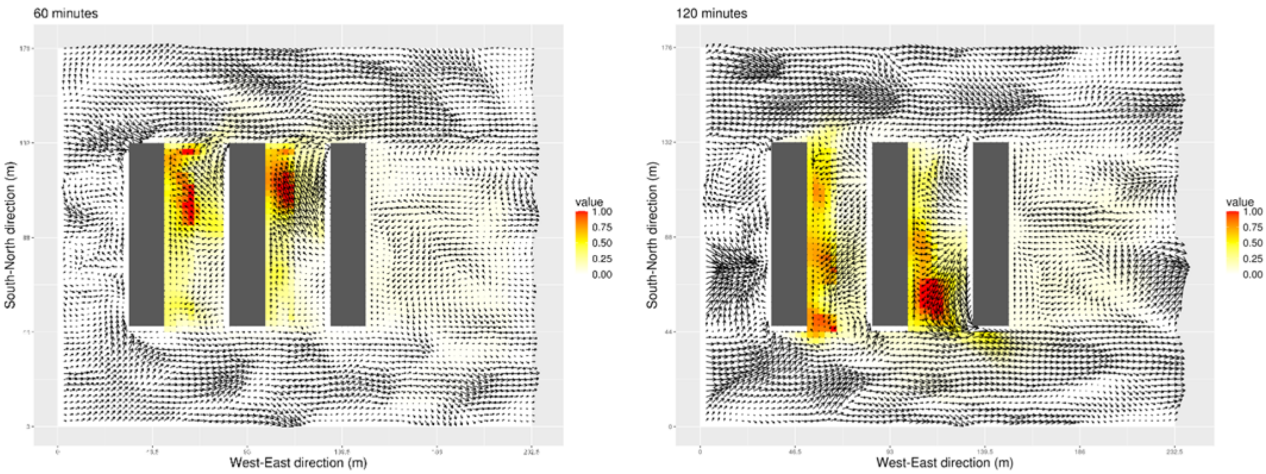
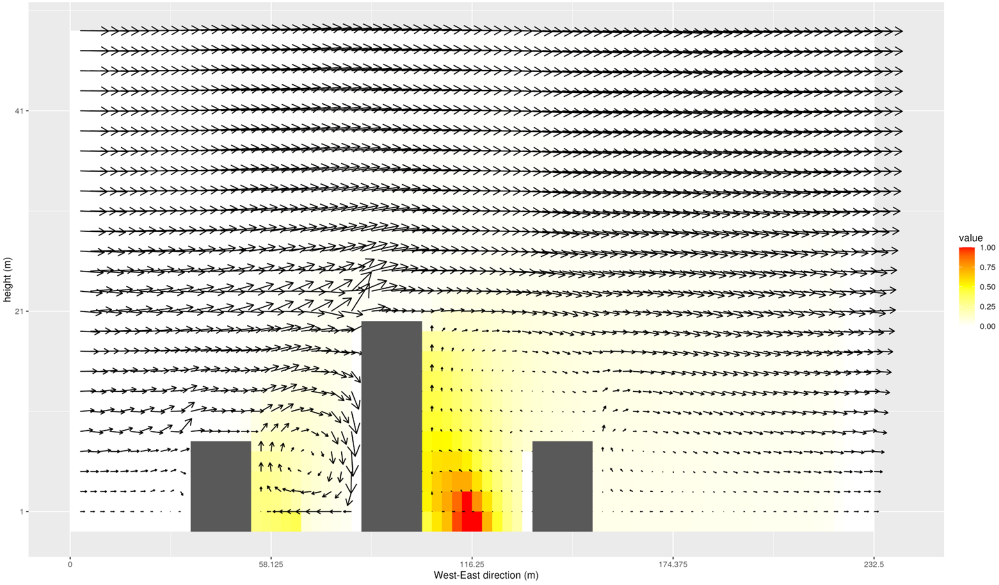


Figure 6, Figure 7 and Figure 8 show the importance of modelling with a high temporal and spatial resolution in a city. There is a lot of variation in the concentration for both time and space. A short clip of this simulation over time can be found at 10.21945/1ccaa275-3ccf-401a-b529-c1eee9035641.

Double street canyon with unequal building height

In this case the first and third building of the street canyon have a height of 8 meter and the second building a height of 20 meter. In Figure 9 a vertical cross-section of the time-averaged concentration and wind velocity are shown. The concentration and the wind speed and direction are averaged along the length of the building.
The concentration is observed to be higher in the second street canyon. In Figure 9 there are multiple vortices observed. The vortices are located at different locations than the case with a double street canyon with equal building heights. In the second street canyon a small vortex with a counter-clockwise rotation is observed near the surface. Above this small vortex a larger vortex with a clockwise rotation is observed. This is also observed for the wake interference flow in Figure 2 downwind of the second building.

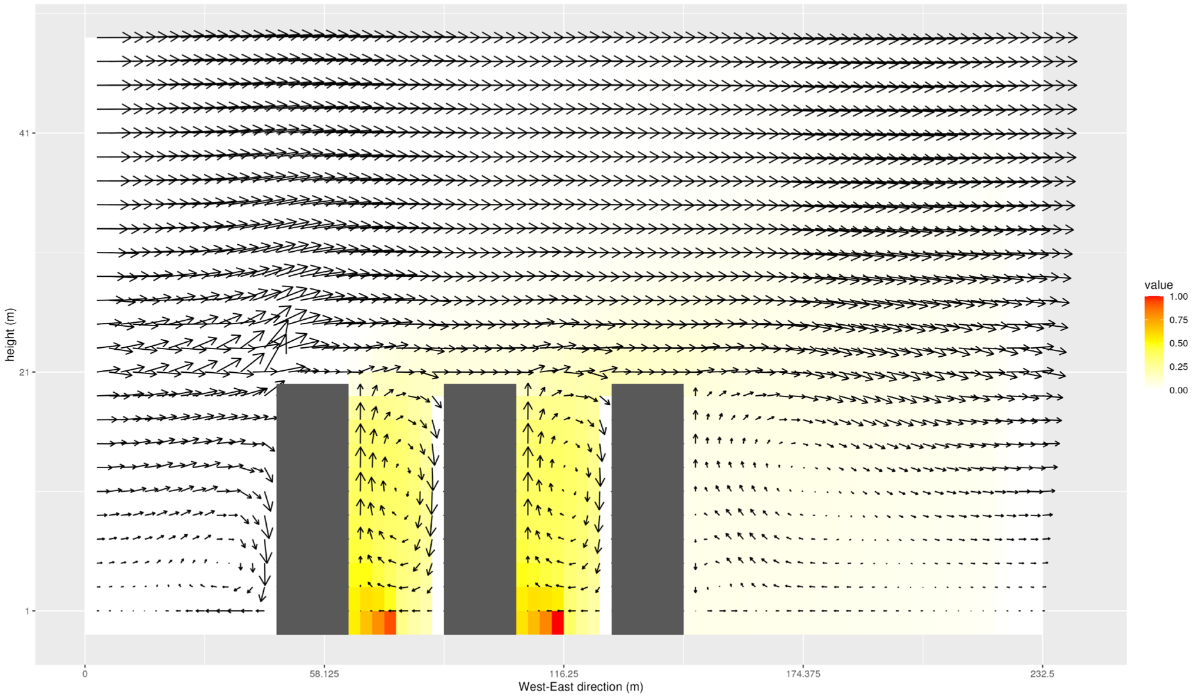
Figure 9 The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and the wind speed are averaged along the length of the building and are averaged over time for the last hour of the simulation.



Narrower double street canyons

In this case the street canyon has a width of 20.3 m instead of 29.1 meter and the building height is 20 m. For this case the ratio W/H is close to one. In Figure 10 a vertical cross section of the time-averaged concentration and wind velocity are shown. The concentration in the street canyons is higher compared to the case with a wider street canyon and the same building height. This is expected because air from above the street canyon mixes less with the air in the street canyon when the street canyon is more narrow.

Figure 10 The color gradient shows the concentration and the arrows show the direction and speed of the wind. The concentration and the wind speed are averaged along the length of the building and are averaged over time for the last hour of the simulation.



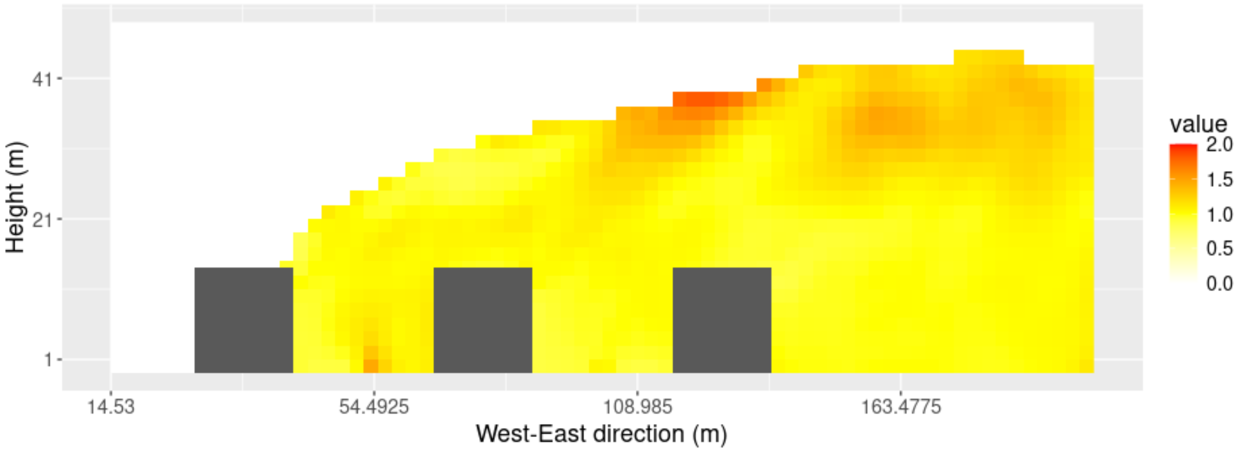
High resolution

In this case the horizontal resolution is twice as high. So, the cell size is 1.45 x 1.45 x 2 meter. The point sources are now placed every fourth cell in the street canyon. Therefore the emission is four times smaller than the emission in the lower resolution simulation. The concentration is multiplied by 4 to compare the concentration more easily with the other cases. The area of one point source in the other cases is equal to four cells in the high resolution case. Another option would have been to add 4 times more point sources. This would result in a fairer comparison, but the run time would increase.

To check if a higher horizontal resolution yields roughly the same results as the standard case in this project, the ratio (high resolution case/ standard case) between the two cases is shown in Figure 11. For the case with the higher horizontal resolution every 2x2 cells are averaged to be able to compare it to the standard case. The concentrations below 0,001 are set to zero to focus on the differences where the concentrations are high.

The ratio between the two cases is largest at locations where both concentrations are relatively low. Also, close to the source a difference is observed. At most locations the ratio is close to 1.

Figure 11 The time-averaged concentration ratio between the high resolution case and the standard case with a building height of 14 meter.



Comparing to wind tunnel data

Comparison to the CODASC Database with W/H =1

The concentration obtained from DALES is compared to a case from the CODASC (Concentration Data of Street Canyons) database. This data base contains wind tunnel concentration data.

To be able to compare the data from the CODASC database with the concentration obtained from DALES, the set-up has to be similar. The wind direction is perpendicular to the street canyon and the ratio between the width of the street canyon and the height of the street canyon is 1. Therefore the case "narrower street canyon II" was used to compare, because the aspect ratio (W/H) is close to 1 in this case.

Even with W/H = 1 and a similar wind direction the case represented by the wind tunnel data and the DALES runs, respectively, differ somewhat. The DALES run was performed for a double street canyon instead of a single street canyon. In DALES point sources were used, while for the wind tunnel experiment line sources were used. The ratio between the length of the building and the height of the building is different. For the wind tunnel experiment this ratio is 10 and for the DALES run this ratio is 4.65.

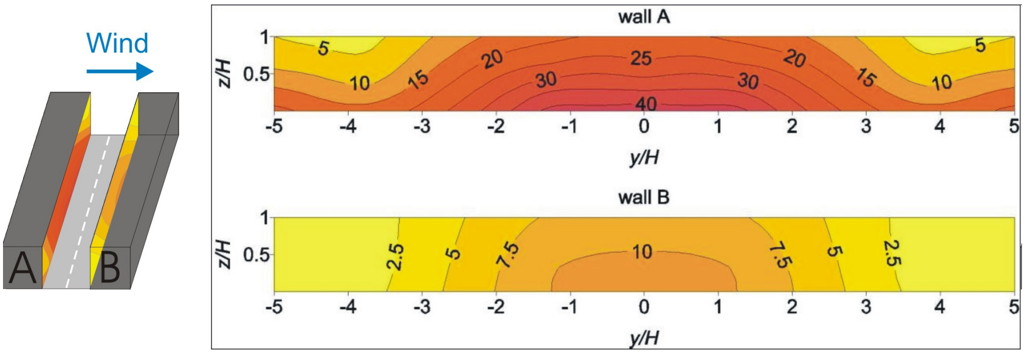
The CODASC data consists of the normalized concentration, the normalized along the street-axis coordinate and the normalized vertical coordinate (Gromke, 2013).

The normalized concentration c^+ is given by

$c^+ = \frac{c\,u_H H}{Q_l}$,

where c is the concentration, u_H is the wind speed of the undisturbed boundary layer at building height H and Q_l is the tracer gas emission line source strength. The normalized concentration for both sides of the street canyon from the CODASC database are shown in Figure 12.

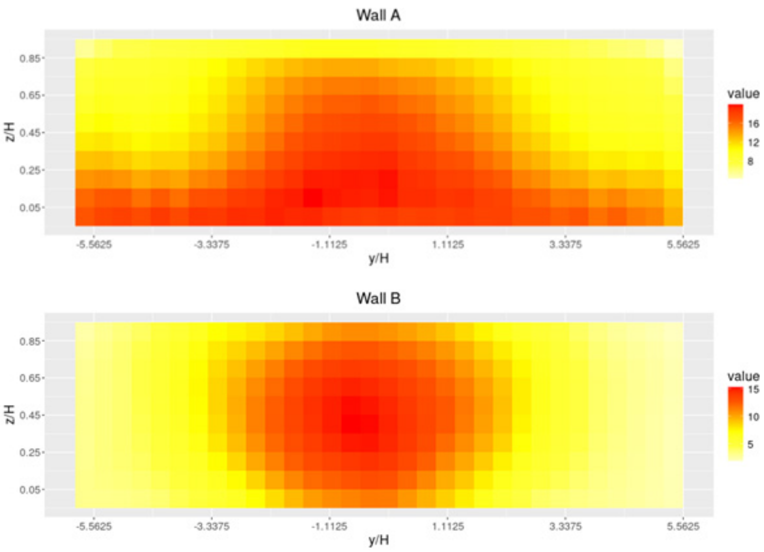
Figure 12 The normalized concentration inside the street canyon for wall A and wall B from the CODASC database (CODASC, 2008)



The normalized concentration for DALES was calculated using a wind speed of 4.73 m/s, which is the average outflow wind speed at the East side of the domain at a building height of 20 meter. The tracer gas emission line source was calculated by multiplying the 16 point sources in the street canyon by the emission strength of 1 a.u./s and by the volume of the cell in which the point source is released and dividing this by the length of the street canyon.

The normalized concentration obtained from DALES is shown in Figure 13.

Figure 13 The normalized concentration inside the street canyon for wall A and wall B from obtained from DALES.

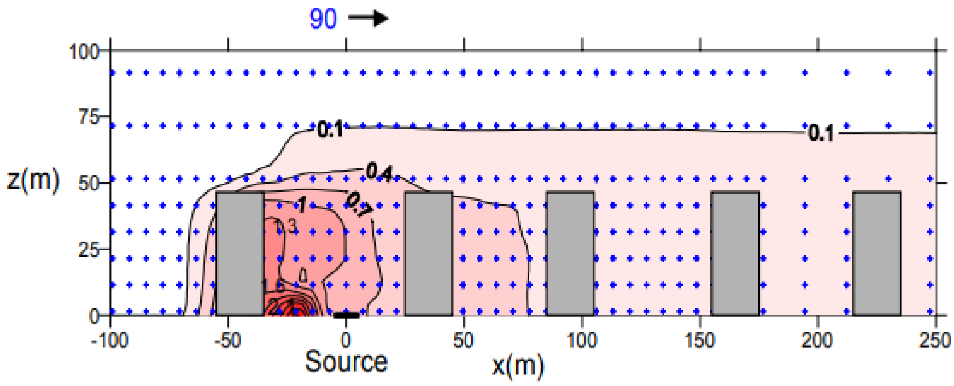


Comparing Figure 12 and Figure 13, the distribution of the concentration is very similar for wall A. The concentration is highest in the middle of the building and at the top left and right the lowest concentrations are observed. However, the normalized concentration obtained from DALES is generally lower than the normalized concentration obtained from the CODASC database. At wall B the highest normalized concentration obtained from DALES is observed at around the middle of the wall, whereas the highest normalized concentration obtained from the CODASC database for wall B is closer to the surface. The normalized concentration obtained from DALES is generally higher at wall B than the normalized concentration from the CODASC database.

Comparison to wind tunnel experiment with W/H = 1.39

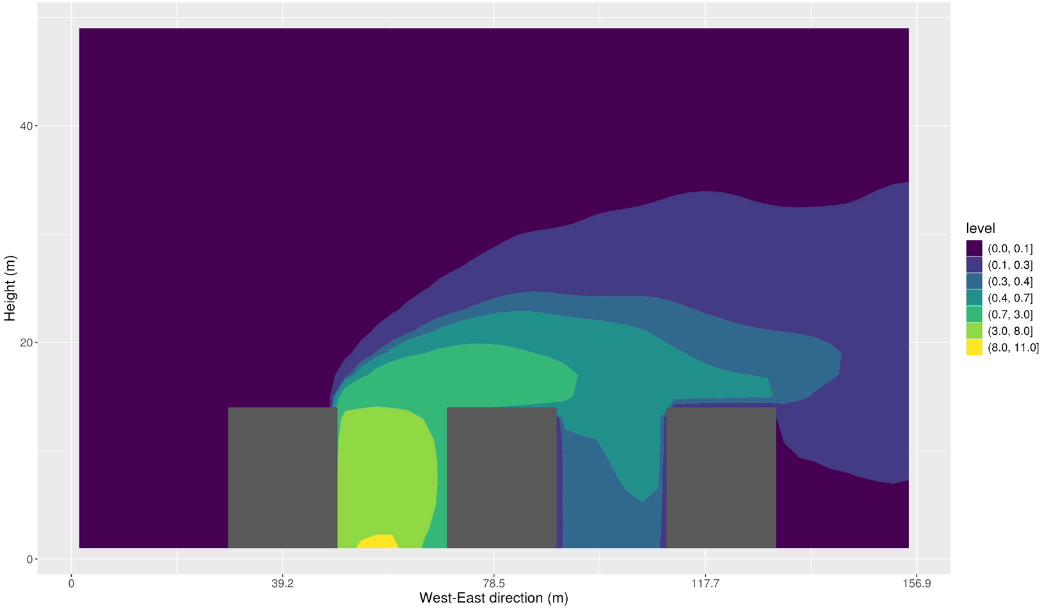
A vertical cross section of the normalized concentration from a wind tunnel experiment described in a paper from Kim et al. (2005) is compared to the vertical cross section of the normalized concentration from DALES. The set up of the wind tunnel experiment is not exactly similar to the set up in DALES. The width to height ratio of the street canyon in the wind tunnel experiment is 1.39, while this ratio for the DALES case is 1.45. The wind tunnel experiment also has more buildings in the domain. The DALES case used here is "narrower street canyon I".
The result from wind tunnel experiments is shown in Figure 14 (Kim et al., 2005).
The definition of the normalized concentration differs from the definition used in the CODASC database. The normalized concentration is given by:
$c^+ = \frac{c\,H\,W\,U_0}{Q}$.
Here, U_0 is the external wind velocity and Q is the tracer gas emission rate.

Figure 14 The normalized concentration obtained from wind tunnel experiments in a street canyon with a width to height ratio of 1.39 (Kim et al., 2005).



To obtain the normalized concentration from DALES the external wind velocity is taken at 15 m (above the buildings), which is 2.2 m/s. It was not specified in the paper at what height the external wind velocity was taken. The tracer emission rate was multiplied by the volume of the cell and the number of sources in the first canyon to obtain a dimensionless concentration. The concentration is averaged along the length of the building. The normalized concentration obtained from DALES is shown in Figure 15.

Figure 15 The normalized concentration obtained from DALES in a street canyon with a width to height ratio of 1.45.



Comparing Figure 14 and Figure 15, the normalized concentration close to the source is higher for DALES. The plume in the wind tunnel is more flat than in DALES, the plume from DALES fans out more upwardly. In the second street canyon the normalized concentration is highest at the West side of the canyon for the wind tunnel experiment, but for DALES the normalized concentration is highest at the East side of the canyon. Lastly, the normalized concentration windward of the first building is higher for the wind tunnel results.

Conclusions and discussion

The DALES model was successfully used to model a street canyon in a neutral boundary layer. The flow around the buildings and inside the street canyons are similar to the patterns found in literature and wind tunnel experiments. It is observed that the concentration is lower in a street canyon with higher buildings, this is opposite to what was expected. It would be interesting to investigate this further. As expected, the concentration is higher in a narrower street canyon with the same building height and length.

A large difference in concentration on the West and East side of the street canyons is observed. Also, it was shown that there is a large variation in the distribution of the concentration over time.

The comparison of the DALES calculations with the CODASC database showed that the distribution of the concentration along the Western wall is similar, but the normalized concentration obtained from DALES was lower for the Western wall and higher for the Eastern wall. At the Eastern wall the highest concentration obtained from DALES is observed at the center of the wall, while the highest concentration obtained from the CODASC database is observed closer to the surface.

The comparison of the concentration in a vertical cross section of the street canyon between the wind tunnel experiment and the DALES simulation shows several differences. The plume fans out more upward in the DALES simulation compared to the wind tunnel experiment. Also the distribution of the concentration in the second street canyon and upwind of the first building is different.

When doing this kind of simulations, using periodic boundary conditions, for a small domain with buildings, it is important to make sure that the wind speed does not reduce too much due to friction. Here, nudging was used to prevent the extreme decrease in wind speed, but in the future it would be preferred to use the geostrophic wind option in DALES. Furthermore, it is important to make the domain large enough, because of the periodic boundary conditions.
For future research, it would be interesting to compare some more cases from DALES to wind tunnel experiments or measurements in a city. Additionally, it would be interesting to study the effects of a different stability of the boundary layer on the concentration in the street canyon. Furthermore, the heat flux from the buildings could be switched on to study the effect of this heat flux on the flow and dispersion in a street canyon.

Acknowledgements

Several recent modules for the DALES model were provided by the Delft University of Technology (TUD), especially the module to implement buildings in the DALES model. The results of the modelling were discussed with experts from TUD and WUR.

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