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TNO report

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The impact of City Trees on air quality in the Valkenburgerstraat (Amsterdam)

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Contents

Samenvatting (Nederlands)

Verbetering van luchtkwaliteit in de Valkenburgerstraat met City Trees
De afgelopen 10 jaar is de luchtkwaliteit in Amsterdam sterk verbeterd. Fijnstof overschrijdt nergens meer de wettelijke norm. De grenswaarden voor stikstofdioxide worden ook nog maar een beperkt aantal locaties overschreden. Het gaat daarbij om locaties met veel gemotoriseerd verkeer, zoals de Prins Hendrikkade, Valkenburgerstraat, Stadhouderskade, Overtoom en Nassaukade. Deze straten maken deel uit van een netwerk met veel verkeer dat dient om de stad voor de auto bereikbaar te houden.
De gemeente heeft een beleid ontwikkeld dat vooral inzet op maatregelen die de luchtkwaliteit in geheel Amsterdam verbeteren. Daarnaast zet Amsterdam zich in om de laatste locaties waar normen nog worden overschreden lokale maatregelen te nemen met als doel hier een versnelling in de verbetering te realiseren. Het aantal mogelijke te nemen lokale maatregelen is echter beperkt. Het verbeteren van de doorstroming is er één van. Er is zeker behoefte aan extra maatregelen. Vanaf maart 2018 wordt is een experiment met een looptijd van 8 maanden uitgevoerd in de Valkenburgerstraat met als doel te onderzoeken of de luchtkwaliteit ter plaatse kan worden verbeterd met lokale maatregelen. Er zijn acht zogenaamde City Trees geplaatst. Deze City Trees bestaan uit roestvrijstalen objecten speciaal ontworpen om lucht te filteren. De objecten van zijn drie meter breed en vier meter hoog. Ze zijn aan twee zijden open en zuigen, met behulp van ventilatoren, lucht door filters bestaande uit mosplanten. Volgens gegevens van de leverancier wordt door deze filters de concentratie fijn stof (PM10) in de aangezogen lucht met 19% verlaagd. Voor stikstofdioxide (NO_2) wordt een verlaging van 5% opgegeven. De gefilterde lucht wordt aan de andere kant (door eenzelfde laag mosplanten) weer uitgeblazen en weer gemengd met de buitenlucht en zorgt zo, in principe, voor verbetering van de luchtkwaliteit.

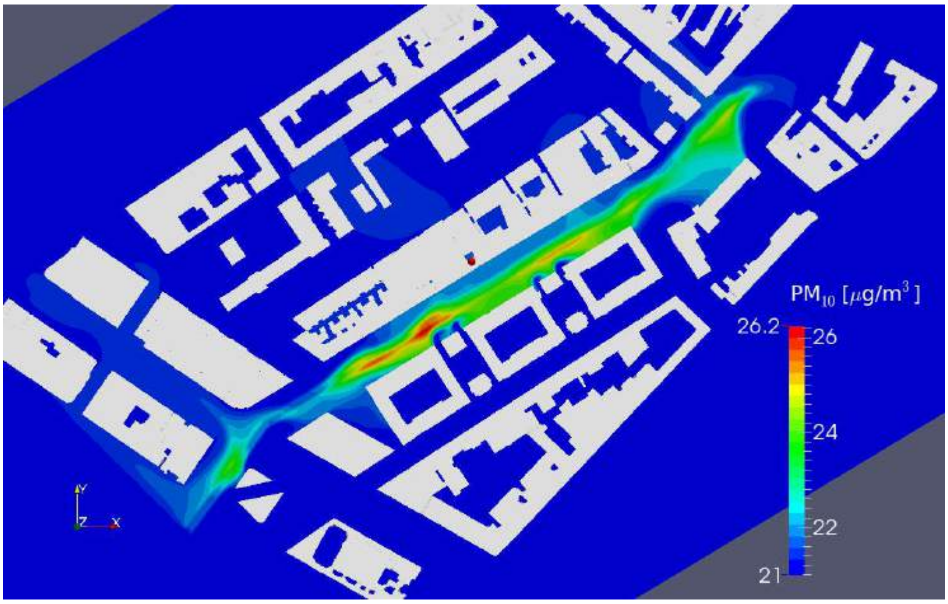
Vaststellen van de activiteit van de City Trees met een simulatiemodel; aanpak
De gemeente wil vaststellen wat de werking en potentie van de City Trees in de praktijk is en heeft TNO gevraagd hiernaar onderzoek te doen. Samen met onderzoekers van de GGD, Wageningen Universiteit en de medewerkers van de gemeente heeft TNO een plan van aanpak ontwikkeld. Daarbij wordt stapsgewijs de werking van de City Trees in de Valkenburgerstraat onderzocht. Het doel van het onderzoek is vast te stellen of met de acht City Trees in staat zijn de concentratie van fijn stof of stikstofdioxide aan de gevels in de Valkenburgerstraat jaar, significant (gedefinieerd als jaargemiddeld tussen 10 en 20 %) te verlagen.

Het meten van een dergelijke verlaging is bijzonder lastig en niet mogelijk binnen het tijdsbestek van 8 maanden dat de City Trees in de Valkenburgerstraat staan. Daarom is er voor gekozen met behulp van een rekenmodel de emissie en verspreiding van stoffen en de invloed van de City Trees te berekenen. Omdat dit met de standaardmodellen voor luchtkwaliteit niet kan is een speciaal model ontwikkeld waar mee zo goed mogelijk de situatie in de Valkenburgerstraat kan worden doorgerekend. Het model berekent de emissies van het verkeer en houdt rekening met de invloed van gebouwen en de rijdende auto's op de verspreiding van stoffen. Door gebruik te maken van gedetailleerde en specifieke informatie over de gebouwen, de luchtkwaliteit in Amsterdam, het verkeer en zijn emissies ontstaat een realistische beschrijving van de situatie in de Valkenburgerstraat. De invloed van de City Trees op de verspreiding van de emissies en effectiviteit kan ook goed in kaart worden gebracht met het model. Dit gebeurt door in de berekeningen de City Trees aan en uit te schakelen. De gegevens over de werking van de City Trees zijn verkregen van de leverancier Green City Solutions. De condities voor de berekeningen zijn zodanig gekozen dat er een optimale kans was op een goede werking van de City Trees.

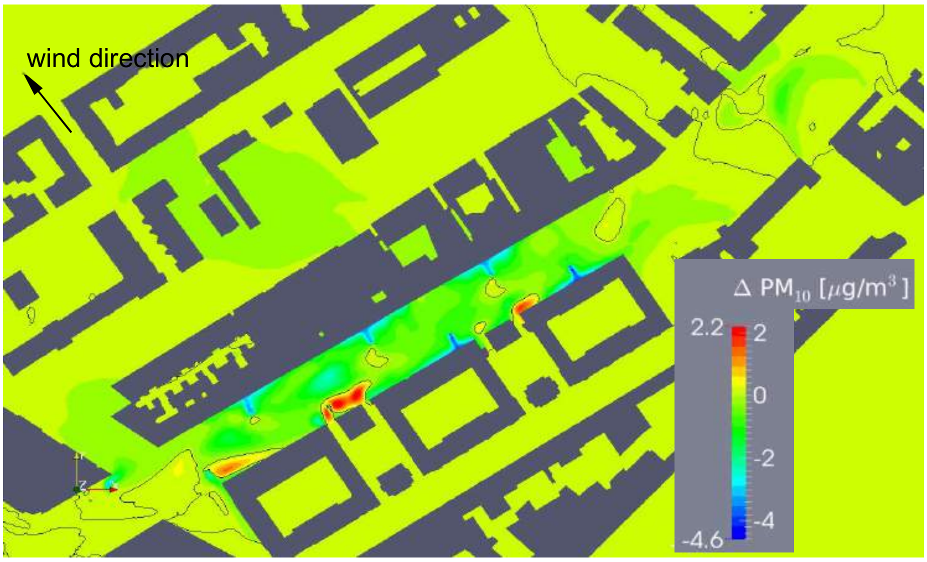
Kwaliteit van de berekeningen

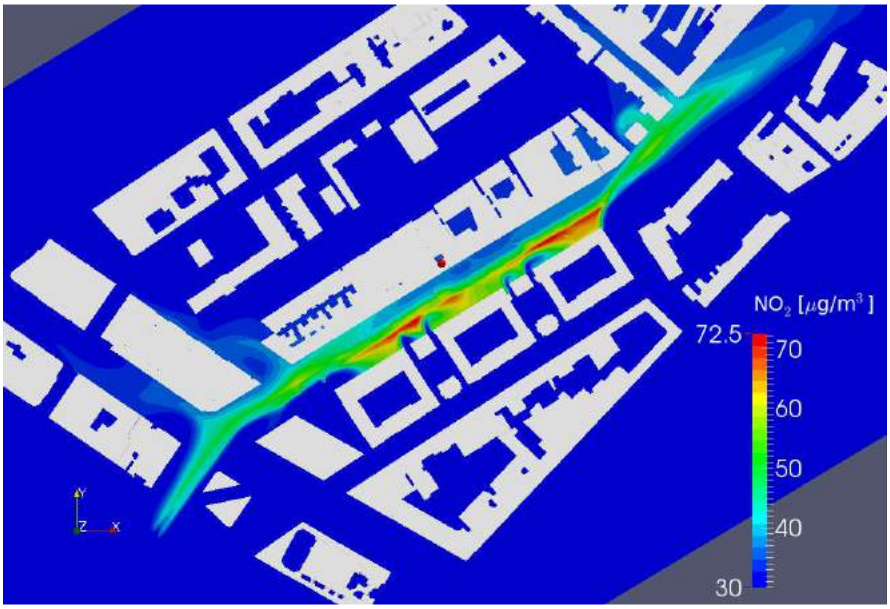
Met het model wordt het ruimtelijk (driedimensionaal) beeld van de concentratie van fijnstof en stikstofdioxide in de Valkenburgerstraat berekend. De berekeningen worden uitgevoerd met City Trees en zonder City Trees. De figuren laat de berekende concentratie in de Valkenburgerstraat met en zonder City Trees zien. Duidelijk is te zien dat ter plaatse van het verkeer (in het midden) de concentraties sterk verhoogd zijn en verder weg van het verkeer (bijvoorbeeld op de stoepen) gelijk blijven aan de achtergrondconcentratie die in de rest van het gebied geldt.

Het verschil in concentraties berekend op de gevels is een maat voor de invloed van de City Trees en dit resultaat wordt dan ook gebruikt voor de beoordeling of er sprake is van een significatie verbetering zoals gewenst.

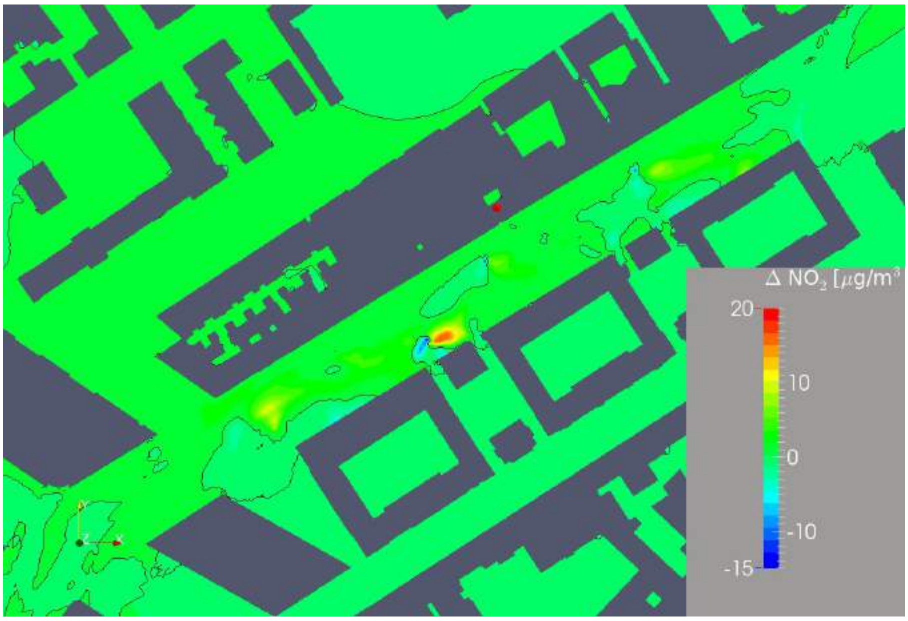


Berekende concentratie van fijnstof (PM10) op 1.5 meter hoogte in de Valkenburgerstraat bij zuidoosten wind (boven) en de invloed van de City Trees op de concentratie,dat wil zeggen het verschil tussen de PM 10 concentratie met en zonder de City Trees; onder)





Berekende concentratie van NO_2 op 1.5 meter hoogte in de Valkenburgerstraat bij zuidoosten wind (boven) en de invloed van de City Trees op de concentratie (dat wil zeggen het verschil tussen de NO_2 concentratie met en zonder de City Trees; onder).



De figuren laten zien dat de concentratie hoog is ter plaatse van het verkeer en dat de City Trees aan de achterkant schonere gefilterde lucht uitblazen. Verder vallen nog wat grillige patronen op die worden veroorzaakt door specifieke luchtstromingen bij zijstraten. De figuren voor NO_2 vertonen een vergelijkbaar beeld. Daarbij zijn de verschillen in concentratie ter plaatse van het verkeer en die bijvoorbeeld op de stoep veel groter. De concentratie midden in de straat loopt op tot 70 $\mu g/m^3$.
De berekende concentraties geven een realistisch beeld de berekende concentraties komen redelijk overeen met concentraties gemeten in straten met een vergelijkbaar hoge verkeersintensiteit.

Berekeningen van het jaargemiddelde effect van de City Trees

De volgende berekeningen werden uitgevoerd:

- Er zijn berekeningen uitgevoerd bij drie omstandigheden: zuidwestenwind evenwijdig met de Valkenburgerstraat, wind loodrecht op de Valkenburgerstraat (zuidoost) en een windrichting daartussenin (zuid). Daarbij werden realistische waarden gekozen voor de achtergrondconcentraties en de windsnelheid. Deze werden afgeleid uit meetgegevens beschikbaar gesteld door de GGD en windgegevens van het KNMI van Schiphol.
- Bij elke windrichting werden berekeningen uitgevoerd: *zonder* City Trees, met *uitgeschakelde* City Trees (dus zonder filtering, alleen de obstakels) en met i*ngeschakelde* City Trees
- De berekeningen zijn uitgevoerd voor fijn stof (PM10) en stikstofoxiden (NO_2)
- Voor fijn stof werden ook berekeningen uitgevoerd met een alternatieve opstelling van de City trees in de straat. De alternatieve locaties van de City Trees werden gekozen op basis van de resultaten van de eerste berekeningen, weergegeven in de figuren. Locaties werden gekozen op plaatsen met hoge concentraties en zoveel mogelijk vóór aaneengesloten gebouwen (d.w.z. niet voor zijstraten)
- Het effect van de City Trees op de concentratie aan de gevels in alle berekeningen werd vastgesteld. Op basis van enkele aannames werd daaruit een ruwe schatting van het jaargemiddeld effect afgeleid. Daarbij werd rekening gehouden met de frequentie van voorkomen van de verschillende windrichtingen.

Resultaten

Uit de vele uitgevoerde berekeningen (alle beschreven in dit rapport) wordt, op hoofdlijnen, het volgende geconcludeerd:

- De berekende concentratieverdelingen in de straat geven een realistisch beeld. De berekende concentraties lijken op concentraties in andere straten met veel verkeer in Amsterdam
- De City Trees leiden tot aanzienlijke verlaging van de concentraties van PM10 aan de uittreed zijde. Aan deze zijde is een pluim van gefilterde lucht zichtbaar die zich verspreidt. De verlaging van maximaal ongeveer 4.5 $\mu g/m^3$ is echter niet uniform in de straat. In grote delen van de straat is de invloed ruwweg 1 $\mu g/m^3$. Deze resultaten gelden bij Zuidoosten wind met doorgaans hoge concentraties. Bij andere windrichtingen met gemiddeld lagere concentratie is het effect evenredig kleiner. Voor NO_2 is de situatie complex. Naast een geringe verlaging van de concentratie wordt ook op een aantal posities een verhoging van de concentratie waargenomen. De centrale vraag richt zich op de concentratie berekend aan de gevels.

- De jaargemiddelde concentratie van PM10 aan de gevels op de begane grond wordt met 0.16 $\mu g/m^3$ *verlaagd* in de aanwezigheid van de City Trees. Dat is minder dan 1% van de concentratie blijkt uit vergelijking met de berekening zonder City Trees. De genoemde getallen zijn geschatte gemiddelden. De berekende waarden bij de verschillende windrichtingen wijken echter niet zeer sterk af.
- Voor NO_2 wordt zelfs een *stijging* van de concentratie met 0.28 $\mu g/m^3$ aan de gevels berekend. Dit hangt samen met het grote verloop van de concentratie van NO_2 in de straat. Ter hoogte van het verkeer worden hoge concentraties tot wel 70 $\mu g/m^3$ berekend. De City Trees zuigen deze vervuilde lucht aan en blazen hem uit in de richting van de gevels en filteren daarbij 5% van de NO_2 uit. De concentratie bij de gevels wordt daardoor hoger dan zonder de City Trees het geval zou zijn.
- De berekende afname van de concentratie onder invloed van de City Trees is voor PM10 het hoogst aan de grond. Op grotere hoogten aan de gevels is de afname kleiner. Voor NO_2 wordt geen sterk verloop met de hoogte berekend.
- Hoewel niet van belang voor beantwoording van de centrale vraag in deze studie is het interessant om te kijken welke fractie van de concentratie bijdrage aan de gevels ontstaan door emissies van het verkeer door de City Trees wordt weggevangen. Gemiddeld is dit door voor PM10 15% met uitschieters van meer dan 50%. Voor NO_2 zijn de resultaten variabel met afnames tot 3.5% en toenames tot 5%.
- Enkele mogelijkheden om de luchtkwaliteit met behulp van City Trees verder te verbeteren zijn onderzocht
    - Berekeningen voor PM10 met een andere positie van de City Trees geven een kleine, niet belangrijke verbetering te zien. De PM10 concentratie daalt op de begane grond 0.22 $\mu g/m^3$ door de City Trees terwijl de daling bij de oorspronkelijk opstelling 0.16 $\mu g/m^3$ bedroeg.
    - Verbeteringen door een verbeterde filtercapaciteit of verdubbeling van het aantal City Trees werd onderzocht aan de hand van ruwe schattingen. Voor PM10 lijkt dit niet te leiden tot het behalen van de doelstellingen van 10-20% reductie aan de gevel. Voor NO_2 zijn de berekeningen complex. Het plaatsen van meer CityTrees leidt waarschijnlijk niet tot verbetering. De verhoging op de stoepen en gevels zal niet veranderen. Het is lastig het effect van verhoging van de filter efficiency voor NO_2 is lastig met ruwe schattingen in kaart te brengen. Nieuwe berekeningen met het CFD-model zouden daarvoor nodig zijn.

De beantwoording van de centrale vraag

Samenvattend kan gesteld worden dat de beoogde verlaging van de PM10 concentraties met de City Trees bij lange na niet wordt bereikt. De concentratie aan de gevels daalt met minder dan 1% terwijl een daling tussen 10 tot 20 % was gewenst. Voor NO_2 wordt zelfs een kleine toename (van 0.5 %) van de concentratie berekend. Beide resultaten geven aan dat met de City Trees de beoogde verbetering van de luchtkwaliteit in de Valkenburgerstraat niet wordt bereikt. De tabel laat alle resultaten nog eens zien.

Verdieping	PM10		NO_2	
[-]	Verandering in Concentratie [µg/m^3]	[%]	Verandering in Concentratie [µg/m^3]	[%]
0	-0.16	-0.80	0.28	0.48
1-2	-0.13	-0.65	0.33	0.54
3-4	-0.10	-0.47	0.37	0.64
5-7	-0.06	-0.31	0.30	0.63

Tabel Schatting van het effect van de City Trees de jaargemiddelde concentratie op de gevels in de Valkenburgerstraat op de verschillende verdiepingen. Negatieve waarden geven verbetering van de luchtkwaliteit aan (daling van de concentratie) Positieve waarden geven verslechtering van de luchtkwaliteit aan: een verhoging van de concentratie

Signature

Delft, 29 March 2019	TNO
P. Saager Research Manager	Andreas Mack and for Jan Duyzer Authors

1 Introduction

Air pollution related to emissions by traffic is still an issue especially in some areas of larger cities. In Amsterdam air quality has improved significantly in the last 10 years. Since several years, air quality limits for particulate matter are not exceeded in the whole city and nitrogen dioxide limits are only exceeded on a few locations. These exceedances (eight sites in total) are found in a few streets with heavy traffic such as the Prins Hendrikkade and the subject of the present study; the Valkenburgerstraat (VS) (see Figure 1). These streets are part of the important core traffic network in the city, needed to keep the city accessible. Since 2005 the city has taken important steps to improve air quality. City wide measures are taken and implemented. Apart from that, local measures are taken to speed up the air quality improvement on these exceedance sites. The number of options however is limited. A few options to lower pollutant concentrations remain, ranging from a ban of cars in the street, improving traffic flow etc. to specially designed devices to filter air. Green City solutions has designed the so called “City Trees” (see Figure 2) that can be used to reduce pollution levels in streets. The municipality of Amsterdam has decided to experiment with these City Trees (CT) and investigate the potential of this technology. Other investigations carried out elsewhere in Europe have shown the potential of this technique to remove particulate matter as well as nitrogen oxide concentrations.
City Trees contain a filter consisting of plants through which ambient air from the street is drawn. Upon passage through the filter, air pollutants are broken down or removed from the air. The cleaned air is again released in the ambient and the concentration of air pollutants in the street is decreased as this cleaned air mixes with the polluted air.
Here we describe the results of a project by TNO looking into the potential of the City Trees to clean air in the Valkenburgerstraat (VS).

Goal of the study:
In the experiment eight City Trees will be positioned in the Valkenburgerstraat (VS) for a period of 8 months on positions selected by the municipality. Several steps will be taken to investigate the potential of the CT in practice. These are described in the work plan drafted by the Municipality. Here we describe our research in which we address the central question: *Can the City Trees have a significant impact on air quality in the Valkenburgerstraat (VS) in representative, and realistic conditions.* Significant was described as: lowering the concentration of particulate matter and nitrogen dioxide at the facades of the buildings in the streets by 10 to 20%. The results of the study will be used by the municipality to decide upon the need for further research and further plans for the City Trees.

Framework of the study
The municipality has commissioned TNO to carry out this study. Scientists from the University of Wageningen (WUR) and the GGD (Public Health Service of Amsterdam) contributed to the approach and design of the study and to the discussions and conclusions on the outcome.
In view of the limited duration of experimental monitoring (8 months) it was decided to assess the effectiveness of the trees for the average annual base by an approach using a simulation model.

The model and the modelled conditions were selected based upon expert judgements by the scientists from TNO, GGD and WUR but also on statistics of concentrations of pollutants in Amsterdam. By doing this, realistic but at the same time and representative conditions were ensured to demonstrate the corresponding operating performance of the City Trees. The studied conditions included situations with low wind speed which were considered best for a good performance of the City Trees

In this report by TNO we present results of the study that consisted of calculations using a detailed CFD (computational Fluid Dynamics) model of emissions and dispersion of air pollutants in the Valkenburgerstraat (VS).

In addition, our methods, are presented and conclusions are drawn.

Figure 1: Location Valkenburgerstraat (VS) in Amsterdam (googleMaps)

Figure 2: City Tree [3]

2 Methods

2.1 Approach

To assess the impact of the CT on air quality in the VS by measurements is difficult. The central question requires a comparison between the situation with and without CT. Such a comparison is difficult because there are many processes that cause y the concentration in the streets to fluctuate. Especially the variations in meteorological conditions make a comparison between situations *with* and *without* CT difficult, if not impossible. From day to day and from year to year the concentration may change dramatically, and it is then difficult to conclude what part of a change in the measured concentration is due to the CTs and what part is due to other causes. Therefore, a model approach was adopted. The model simulates the real situation as good as possible and provides the possibility to switch the CTs on and off in the model run. The difference between the concentration calculated with and without then reflects the impact, given the selected filtering capacity of the CT. This approach is followed in this study.
The model included a description (with respect to dimensions, flow characteristics and filtering efficiency) of eight City Trees distributed near the traffic lane in the street. Conditions for the calculations were chosen with the aim demonstrate the operating performance of the CT on air pollution levels for representative situations. These included conditions with low wind speed favourable for a good performance of the City Trees.
To calculate the dispersion in such a complex situation and calculate concentrations at every spot in the street a model is required that takes all these processes into account. Classical models to calculate air concentrations in streets (such as the well-known and prescribed CAR model [1]) are not able to take filtering and the influence of obstacles into account. Therefore, in this study, a CFD (Computational Fluid Dynamics) model was developed and applied.

2.1.1 Processes and the model

The concentration of air pollutants in the VS is determined to a large extent by:
- The background concentration (polluted air flowing from the rest of the city of Amsterdam and the region surrounding the city, into the street)
- The concentration caused by emissions of traffic in the street

The polluted air coming from traffic is mixed by the wind and related turbulence and diluted. This leads to a situation where the highest concentration is found near the driving lane (the road) with traffic and a lower concentration in the rest of the street. How well mixing takes place depends on the wind and turbulence. However, mixing is also influenced by houses in the street (and other obstacles such as trees) and by traffic that is also generating air flow and turbulence. The CT are placed near the road and draw air from that location. How much pollution is drawn into the CT depends on the exact location and the concentration at that location.

The latter concentrations therefore depend on the parameters mentioned above. A CFD model divides the whole area in small cubes (in this case millions). The mass and momentum flow in all individual cubes is calculated using basic equations based upon laws from physics.

By doing this for example the influence of houses on wind flow can be taken into account etc. The calculations in all individual cubes are combined and this results in a three-dimensional (3D) picture of the concentration of the pollutant on every spot in the street and its surroundings. The City Trees and their effect (drawing in polluted air and expelling filtered air) can be placed in the streets and model calculations can be carried out with and without them working. In that way the impact of the CT on concentrations may be assessed.

To carry out the calculations the OpenFoam open source software package [2] was used. Input parameters to the model are:

- The wind speed and direction
- Background concentrations of selected pollutants
- Emissions and statistics of intensities of traffic in the Valkenburgerstraat

The model is described below in paragraph 2.3. The values chosen for background concentrations etc are described in the paragraph 2.4.

2.1.2 *Model conditions*

The conditions chosen for the calculations may, to some extent, be relevant to the outcome of the calculations. Wind direction and speed are relevant parameters. The background concentration is relevant because CT not only filter freshly emitted pollutants but also background air that is mixed in the VS with the traffic emissions. Especially for particulate matter the contribution of the background is dominating the concentrations in the Valkenburgerstraat.
The amount of pollutants emitted by traffic in the street is also important because this determines the pollution concentration gradients in the street (high levels of nitrogen oxides near the traffic and lower away from the traffic) These gradients are relevant since they interact with the position of the CT in the street. The ideal location of the CT is close to the released emissions to filter air where the concentration is highest.
For all these parameters best, available parameters are used in the calculations:

- Background concentrations from measurements at the city background site in Vondelpark
- Wind speed and directions from Schiphol converted to windspeed above the city
- Traffic intensity, velocity and emission factor according to recent inventories by TNO
- Parameters describing the filter and flow capacity were obtained from Green City solutions.

These conditions guarantee a realistic simulation for the model runs. In practice, optimal parameters were chosen to describe the capacity of the CT. The idea was that if with these favourable filter efficiency, the air pollution is significantly reduced these parameters would have been subject to further assessment in practice as taken up in the project plan. The parameters observed in practice could then easily be used in a few new runs with the model. Likewise, if the results would have been negative there is no need to carry out new calculations because optimistic parameters were chosen.
In practice three conditions were simulated with the model:

- Wind perpendicular to the street (i.e. South-easterly winds). In this run a low wind speed was used and the background concentration was high

- Wind in line with the street (i.e. South- westerly winds). In this run a relatively high wind speed was used and the background concentration was low
- Southerly winds with moderate wind speeds. This represents an intermediate flow condition with approximately average conditions.

By doing this the effect of the City Trees is calculated in a representative manner:

- The south easterly winds provide the conditions with wind perpendicular to the Valkenburgerstraat. In these conditions a so-called *street canyon* situation is developed in the street. These conditions normally lead to the highest concentrations in a street. In those conditions with low wind speed the CT could have the largest impact.
- The south westerly condition is a condition that normally lead to low concentrations.
- The southerly conditions represent the situation in between the two extremes

It is assumed that by simulation these three conditions the whole range of conditions is covered. In addition, it may be argued:

- The three wind directions cover all wind relevant directions. From considerations of symmetry southerly winds with respect to the Valkenburgerstraat are more or less equivalent to Northerly winds and similar reasonings hold for South-Easterly winds and North Westerlies as well as South-Westerlies and North-Easterlies

Three runs were carried out for each of those conditions:

- No City Trees in the VS
- Eight non-active City Trees in the VS only affecting the flow as obstacles
- Eight active City Trees in the VS, interacting with the flow and actively filtering the polluted air

In all cases realistic traffic intensities with corresponding emissions were simulated. More detail on the parameters used is given below.

The accuracy of model calculations is difficult to discuss in the absence of measurements in the Valkenburgerstraat. A comparison may be made with concentrations measured in other streets with heavy traffic. The value of this comparison however is of course limited.

2.2 General setup and characteristics of the City Trees

Figure 1 shows the Valkenburgerstraat and is position in Amsterdam. Figure 2 shows an isolated City Tree. The characteristics of the City Trees were all obtained from Green City Solutions the manufacturer of the objects. These included physical dimensions, the forced air flow through the moss filters and the filter efficiency for nitrogen dioxide (NO_2) and particulate matter (PM). In this preliminary study no measurements were carried out to check the provided values. In the work plan such measurements would be carried out in the next step only if the model calculations would show that City Trees have a large potential to reduce the pollutant levels in the VS.
The City Trees were positioned in the VS as shown in Figure 3 Note the numbering of the City Trees as they are referenced in the text.

At the City Trees, a constant normal velocity of 0.5 m/s is forced at the in- and outflow of the filter surfaces. All City Trees are arranged such that the direction of the airflow is from the street to the buidling facades. For PM10 the filter efficiency is given as 19% and for NO_2, the filter efficency is given as 5%. These values are based upon information provided by Green City Solutions. For the additionally formed NO_2 from reactions between nitric oxide (NO) and ozone (O_3) (as explained below) the efficiency is also taken to be 5%.

The geometrical setup of the City Trees was taken from Green City solutions [3]. The height is 4.11 m, the width 2.93 m, the dimension of the filter area is 2.63 m x 2.63 m.
Information on the locations of the eight City Trees was provided by the municipality of Amsterdam. Since the City Trees are placed in between real trees and these trees might have influence on the flow topology in the VS, 40 trees were included in the model as porous structures; the positions are taken as given in Figure 3.

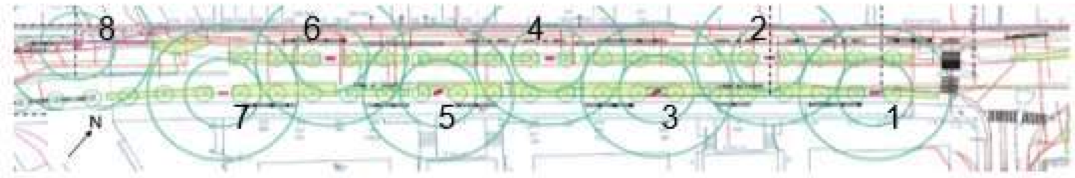


Figure 3: Position of city trees in VS

2.3 Geometry and CFD setup

The geometrical information of the VS was obtained from 2D GIS data (buildings) of the city of Amsterdam [4] combined with the heights of the buildings which is taken from the actual height map of the Netherlands (AHN, [5]). The building shapes and heights in the VS compared with Google Street view data and corrected to have a representative and actual geometry of the VS in the part where the CT will be positioned. The actual setup of the geometry includes the buildings at the Valkenburgerstraat and, depending on the topology, one or two additional blocks of buildings around it. The overall dimension of the area discretised with buildings is approximately 600 m x 400 m.

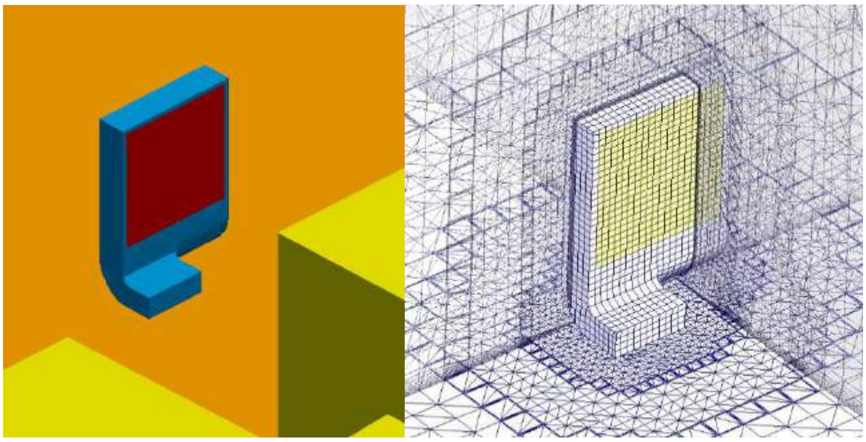


Figure 4: City Tree geometry (left) and CFD grid (right)

The geometries were discretized in a CFD (Computational Fluid Dynamics) mesh domain of 900m x 600m and a height of 200m.
All grids were generated as hybrid hexahedra dominant meshes by snappyHexMesh (included in OpenFoam [2]). They contain approximately 6.1 million cells (4 million nodes). Away from any geometrical features, the cell edge length are 16 m; at the surfaces, the cells are refined up to 0.1m on the City Trees. All surfaces feature 6 wall normal layers in order to resolve the boundary layers accurately. In addition the geometrical features as buildings and the City Trees, 40 real trees were included as porous zones in the model as explained earlier. To model the effect of the vehicles, traffic zones were modelled in the VS which add momentum and turbulence due to the drag of the vehicles according to [6]. The emissions were introduced by a second traffic zone located close to the ground where the emissions are released. For both momentum and emissions actual values for north and south bound traffic lanes were applied. The location and dimension of the traffic zones are shown in Figure 6. By this, the contribution of the emissions in the VS is modelled; the contribution of the surrounding area is modelled by the background concentration which is applied at the boundaries.
At the inflow boundaries of the CFD domain a representative atmospheric boundary layer is applied to the model (see below).

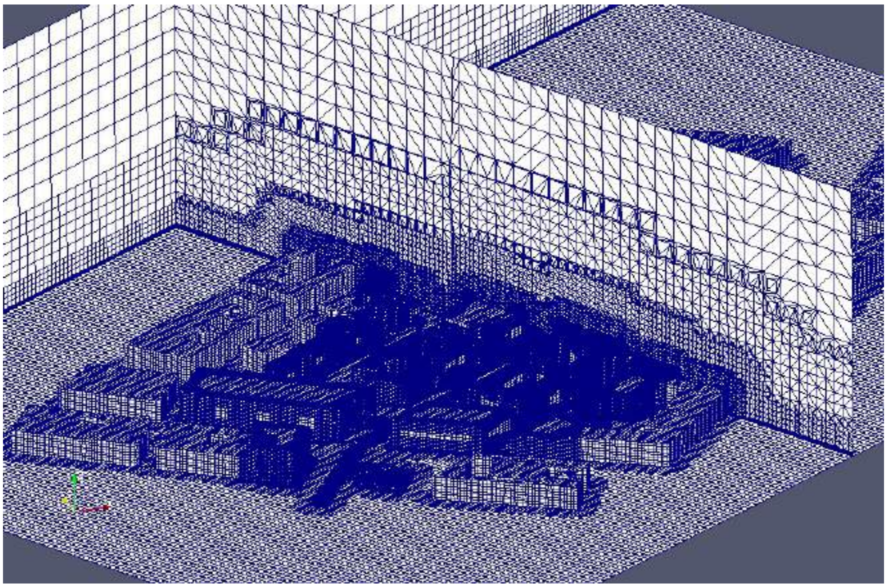


Figure 5: CFD mesh

Figure 6: Traffic zones introduced in the CFD model for north (blue) and south (purple) bound traffic

All flow calculations were performed with SimpleFoam [2], a steady state solver of the Navier Stokes equations applying a 2nd order discretisation scheme; the turbulence was modelled applying the k-ε turbulence model. The dispersion calculations were performed as a passive scalar transport on the calculated flow field including turbulent transport (adapted version of scalarTransportFoam). All emissions were released in the predefined traffic zones. The background concentrations of the species were applied according to the flow condition (see also Table 1).
The calculations were carried out for PM_{10}, NO_2 and NO. Assuming fast reaction of NO with O_3 (ozone) to NO_2 the NO distributions were converted to NO_2 concentrations according to the following relation[1] according to [7]:

$$C_{formed}(NO_2) = 0.6 * C_{BG}(O_3) * C_{traffic}(NO)/(100+C_{traffic}(NO))$$

All concentrations are in µg/m^3.
$C_{traffic}$ (NO_2) is the formed NO_2
$C_{BG}(O_3)$ is the background O_3 concentration
$C_{traffic}$ (NO) contribution of traffic NO

Here, the NO concentration of the traffic is calculated as the difference of the given NO_X and NO_2 concentration.

$$C_{traffic}(NO)=C_{traffic}(NO_X)-C_{traffic}(NO_2)$$

The total NO_2 concentration is calculated as the sum of the NO_2 directly emitted by the traffic and the NO_2 formed from the reaction of NO with ozone:

---

[1] This is essentially a best-case approach. More NO_2 is formed because of this assumption than is actually formed. This is beneficial for the impact of the CT because the filtering capacity for nitric oxide NO is zero.

$C_{all}(NO_2)=C_{traffic}(NO_2)+C_{formed}(NO_2)$

As an example, for the present cases the direct emission of NO_2 leads to NO_2 concentrations up to 90 µg/m³. The emissions of NO lead to concentrations of approximately 150 µg/m³. Therefore, the NO_2 formed from NO and O_3 contributes with up to 15 µg/m³ which means an additional 15% (O_3 background concentration 41 µg/m³). With a O_3 background concentration of 30 µg/m³, the additionally formed NO_2 would be approximately 11 µg/m³.

2.4 Meteorological conditions, background concentrations and vehicle emissions

The CFD calculations requires realistic information on: air flowing in from other streets (background), wind speed and traffic intensities, speed and emissions. Together with the information on buildings this completes the information to calculated the concentrations in the VS in three dimensions (3D)

2.4.1 Meteorological information

-The goal was to select representative conditions (wind speed and background concentrations) for three different wind directions (one perpendicular to the VS, one in line with this street and one direction in between). A relatively low but realistic wind speed would be selected that allows the City Trees to do what they are supposed to do: lowering pollution concentrations. Conditions with low windspeeds would be beneficial for the City Trees performance yet at the same time they are important because low wind speeds may lead to high pollutant concentrations

In addition, the 2016 *meteorologica*l data from Schiphol airport was used (hourly data from KNMI). These data from Schiphol are transformed to values for Amsterdam city according to a standard procedure to be used in the CFD modelling: First the windspeed is converted to a reference height at higher level based on roughness conditions for Schiphol. Then the wind speed is converted to a windspeed at a level needed for the CFD model using roughness conditions for the city of Amsterdam. For the CFD calculations, a wind profile taking the wind speed and surface roughness length into account is applied at the inflow domain. Figure 7 shows the frequency of the occurrence of wind directions at Schiphol whereas Figure 8 shows wind speed.

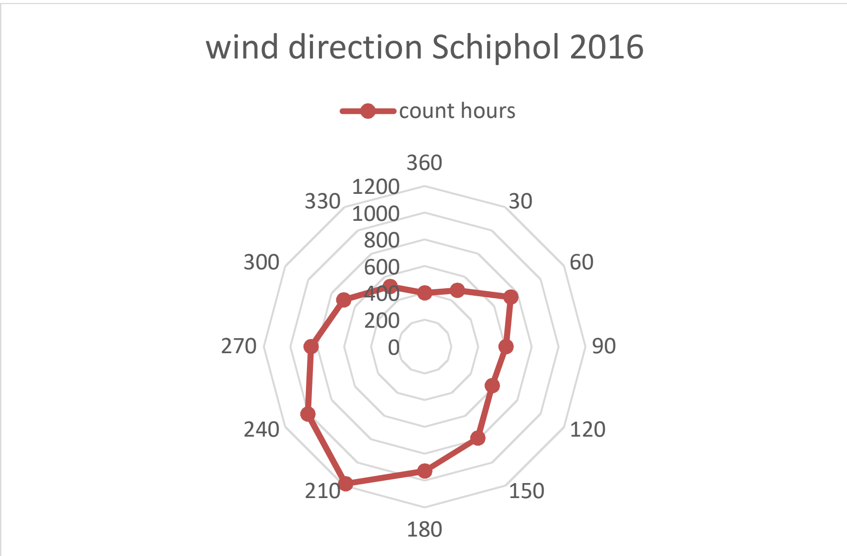


Figure 7 Frequency of occurrence of wind directions at Schiphol In 2016

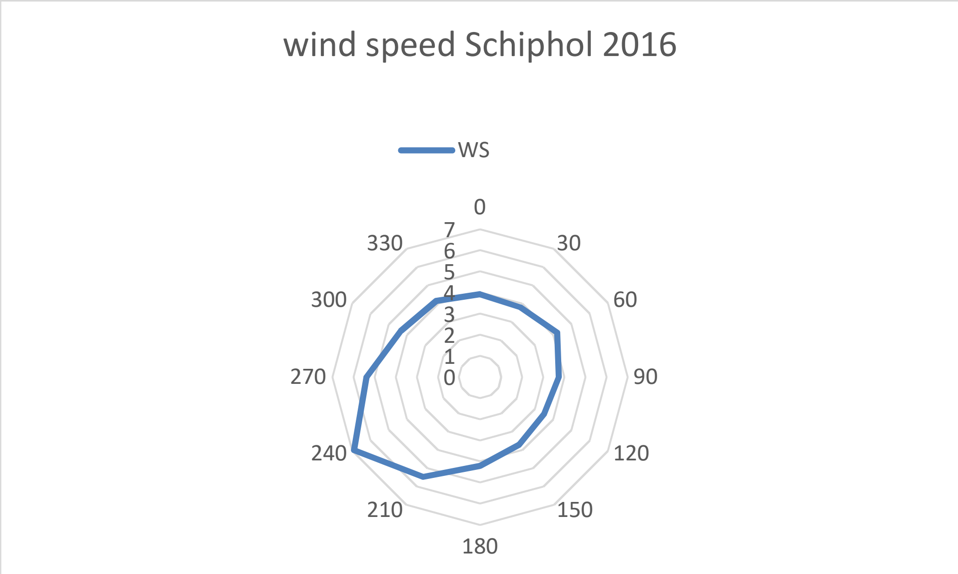


Figure 8 Windrose for Schiphol. Average windspeed at a given wind direction

2.4.2 *Background concentrations*

The *background* concentration levels are based on measurements from 2016 carried out in Amsterdam and provided by the GGD Amsterdam. This institute carries out the monitoring in the city. The data was provided for the van Diemenstraat (a heavily polluted street and considered also representative for the Valkenburgerstraat) and Vondelpark (considered as a background reference station).

Figure 9 shows the average concentration of PM10 as a function of wind speed observed at Schiphol in 2016. These conditions are assumed to be similar for Amsterdam. South-westerly wind conditions are present frequently. South-easterly winds occur less, but are still not exceptional.
Figure 10 shows the concentrations of PM10 as measured in the van Diemenstraat (considered representative for the VS) and Vondelpark (considered representative for Amsterdam background).
The highest background concentrations occur at wind speeds of approximately 2 m/s and a wind direction of 150° which corresponds approximately with the flow direction perpendicular to the VS (run 1). This wind speed is slightly lower than the yearly averaged value in Figure 8 (3.5m/s). In order to have a favourable wind condition for the CTs, the wind speed of 2m/s and corresponding PM10 background concentrations were chosen (compare also Table 1).

For the two other wind directions (239°, approximately wind from south-west, run 2 and 194°, run 3) the wind speed and background concentration are taken from to the annual average of the corresponding wind direction.

The NO_2 background concentrations used later on are also based on the annual average of the corresponding wind direction (compare Figure 11).

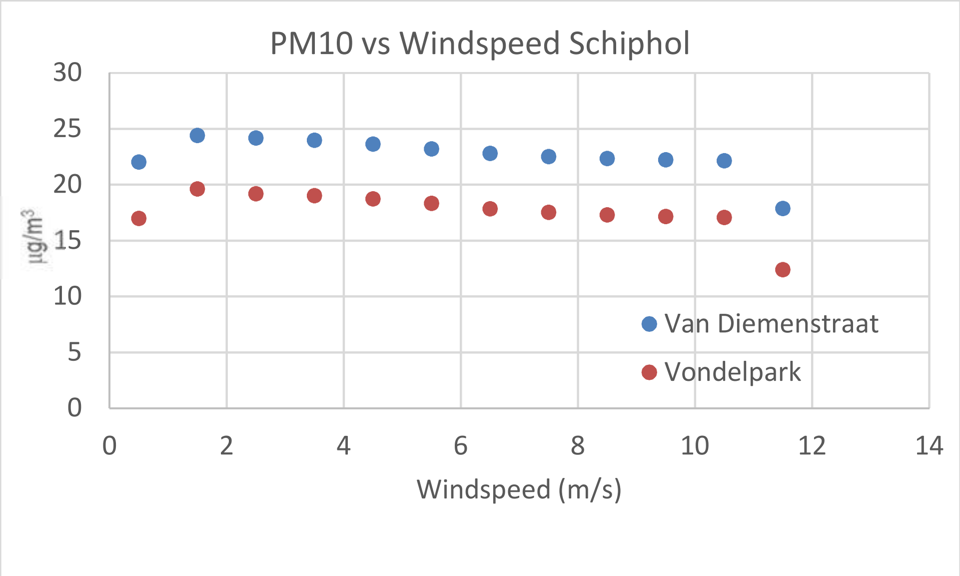


Figure 9 PM10 concentration versus (windspeed at Schiphol in 2016)

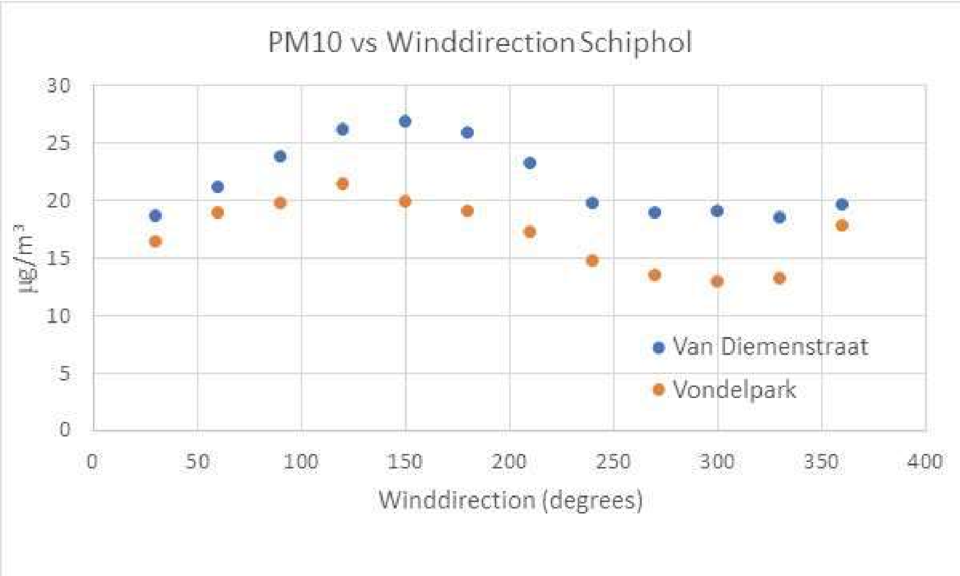


Figure 10: Concentration of PM10 in the Van Diemenstraat en Vondelpark in 2016

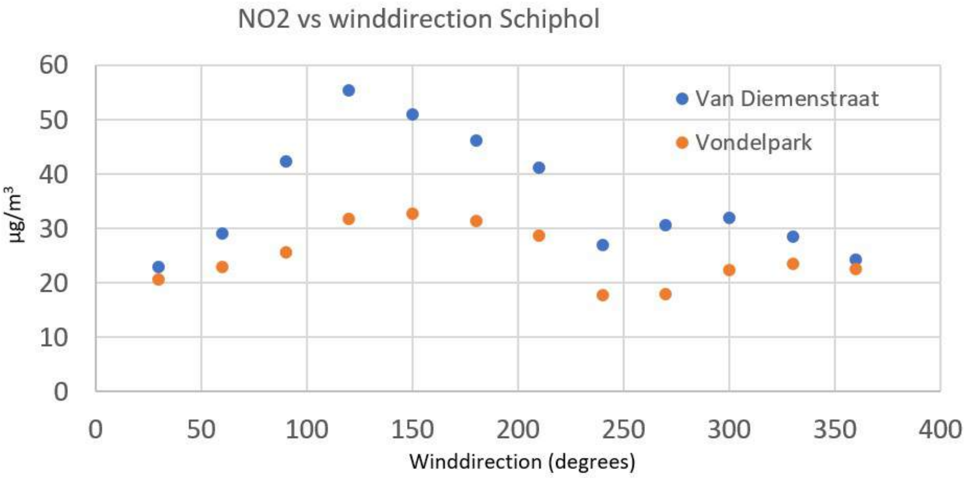


Figure 11: Concentration of NO_2 in the Van Diemenstraat and Vondelpark in 2016

Based on this information the following selection was made for the calculations.

Table 1 shows for the three runs the wind direction, the wind speed, the concentration of PM10 and NO_2 in background air and the concentration (target) that might be reached in the VS when the emissions of the traffic are added to the background. The latter concentration is based on concentrations observed in the van Diemenstraat and does not play a real role in the process. It is just mentioned here as a reference. The model runs with both background emissions and emissions from traffic in the street would need to show concentrations similar to these target levels observed in the van Diemenstraat. In the absence of monitoring in the Valkenburgerstraat is this the best possible verification of the results of the calculations.
It is assumed that the impact of the City Trees will be largest in conditions with little wind and turbulence. By this selection, two extremes conditions are covered in the study. Wind perpendicular to the street (with a low wind speed) lead to limited mixing whereas the conditions aligned with the street (and higher wind speed) lead to more mixing (with low concentrations) It is assumed that other conditions (wind directions and wind speed) will lead to results that lie in between these two extremes. The calculations with Southerly winds show a condition in between the two rather extreme values

Table 1 Values for input parameters to be used in the two base runs with the CFD model

Parameter	Input run 1	Input run 2	Input run 3	Units
Wind direction	149[2]	239[3]	194[4]	Degrees
Wind speed selected at Schiphol	2	6	4.3	(m/s)
Wind speed CFD simulation above VS	1.2	3.6	2.6	(m/s)
PM10 background	21	15	18	(μg/m³)
PM10 target	26	20	24	(μg/m³)

[2] perpendicular to VS
[3] in line with VS
[4] 45° with respect to VS

NO_2 background	32	18	30	(μg/m^3)
NO_2 target	55	30	44	(μg/m^3)
O3 (background)	41	41	41	(μg/m^3)

The ozone background concentrations were taken as annual averages (data from 2016).

2.4.3 *Emissions*

The emissions from the road traffic in the VS are based on TNO data acquisition in the VS performed in 2016 and 2017 [7]. Based on the collected data of the number plates which were linked to the vehicle emissions, accurate estimations of the emissions were obtained. For north and south bound traffic, standard Dutch emission factors of four different vehicle classes (cars, light trucks, heavy trucks and busses) were taken into account. A fifth class of vehicles where the number plate could not be identified were redistributed amount the other classes (typically 720 out of 12.000 per day).
The available data was averaged over the 2016 and 2017 measurement period applied to the traffic zones.
The vehicle average velocity was based on available data measured during rush-hour (16.00h-18.00h) on working days.

Table 2: Typical vehicle categories contributions for the VS per day (2016 data)

vehicle category	counts per day north bound	counts per day south bound
car	11778	8297
medium trucks	54	38
heavy trucks	41	30
busses	109	65

Table 3: Emissions of the traffic in VS [μg/s] and average traffic speed

direction	PM_{10}	NO_2	NO	velocity [km/h]
Northbound	731	698	2390	19.5
Southbound	872	933	1865	16.5

3 Results

To assess the potential impact of the City Trees to reduce pollutant concentrations in the VS calculations with three representative wind directions were carried out. With the South-eastern wind direction, a typical street canyon situation is investigated. For the second wind direction (south west) the main flow direction is aligned with the direction of the VS. Finally a third (intermediate) wind direction was investigated.

3.1 Wind direction South-East: street canyon flow

At a wind direction from south-east the orientation of the wind is perpendicular to the street. The buildings in the VS then form a typical street canyon situation with a large vortex being present in the street (Figure 12). Typically flow from the surroundings enters the street canyon at the downwind facades, moves upstream close to the street and moves upwards at the upwind facades to be entrained again into the large vortex. Typical local wind speeds for the chosen wind condition are in the range of 0-1m/s inside the street canyon vortex. The velocity above the buildings is higher and is driving the street canyon vortex.

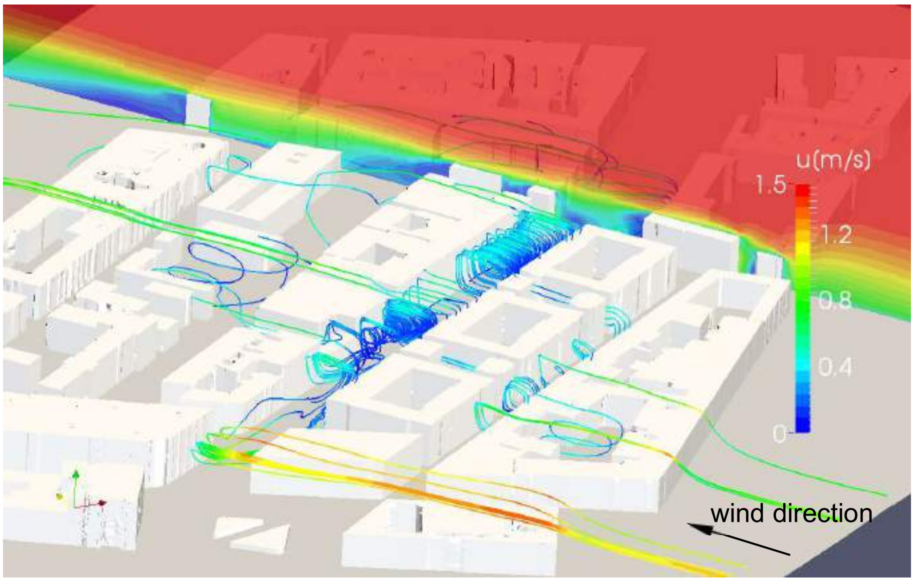


Figure 12: Flow topology in VS (wind south-east) shown by velocity on streamlines and plane.

Considering the local wind speed at a height of 1 m and 5 m, main features of the flow topology can be identified. Since the global flow speed in the street canyon is low, the traffic has an impact on the local flow velocity and direction. Therefore, the effect of the traffic lanes can be seen in the local flow speed (Figure 13) since the vehicles add momentum (and turbulence) to the flow.
The effect of the (normal) trees, modelled in the CFD solution as porous structured adding aerodynamic drag to the flow, can be seen due to a decreasing local flow velocity at the height of the crown (Figure 14). Behind the crowns wakes can be identified. The trees do not influence the street canyon flow topology strongly but decrease its velocity.

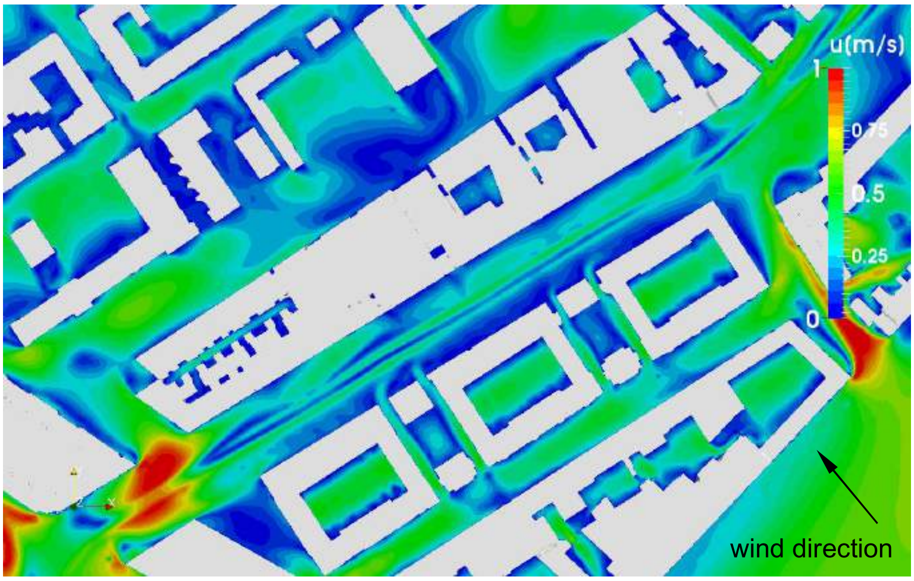


Figure 13: Velocity distribution at 1m height (vehicles)

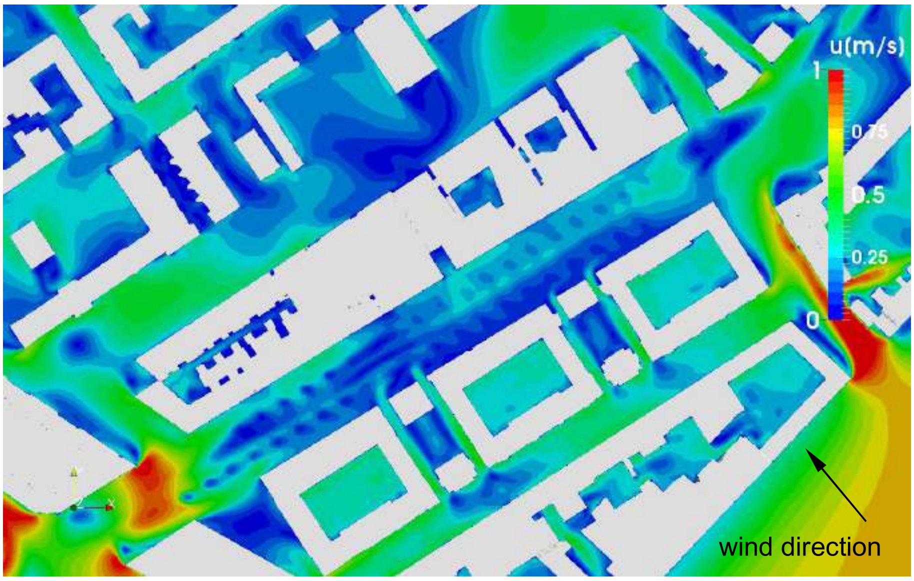


Figure 14: Velocity distribution at 5m height; effect of tree crowns can be identified

The presence of the eight City Trees does not change the global flow topology in the street canyon significantly (compare Figure 15 and Figure 12).

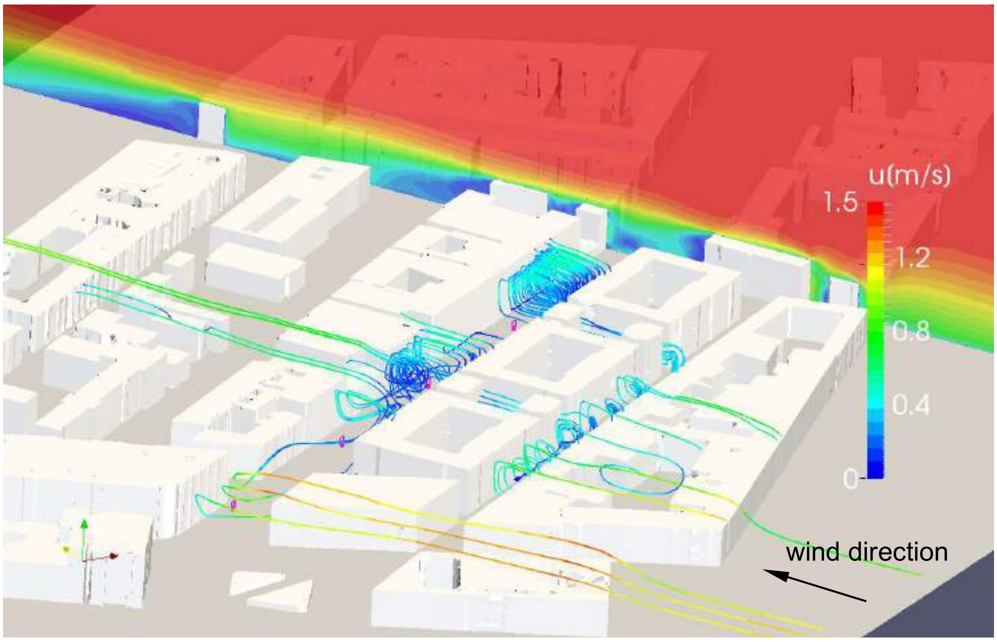


Figure 15: Flow topology with City Trees in VS (wind south-east) shown by velocity on streamlines and plane.

To quantify the presence of the City Trees on the PM10 distribution and its capability to remove PM10 vehicle emissions, three dispersion calculations were performed. A first one, the reference setup without the City Trees, a second one where inactive City Trees were placed into the VS and a third one with active City Trees including ventilation and filtering.

The PM10 distribution at a height of 1.5 m in the reference case has a maximum PM10 concentration of 26.2μg/m^3 in the centre of the road (Figure 16). Outside the street canyon, where open areas due to streets or low buildings are present, the street canyon vortex is broken up and emissions disperse more rapidly.
This seems to be reasonable concentration compared to concentrations observed in the van Diemenstraat where 26μg/m^3 was observed with this wind direction.

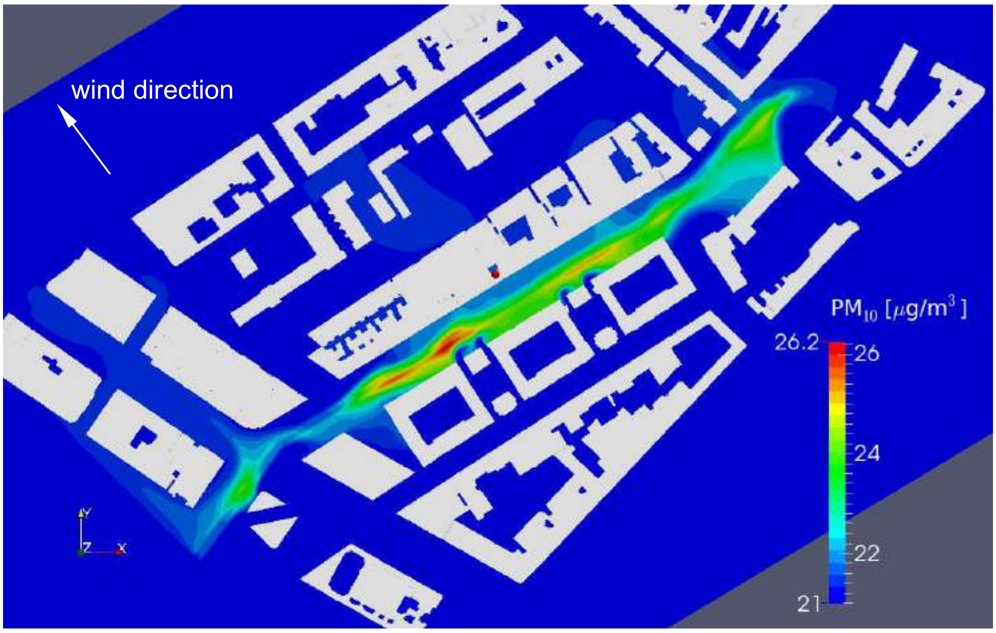


Figure 16: PM 10 concentration distribution at 1.5 m height (no City Trees, reference case)

As already discussed for the flow topology, the presence of inactive City Trees does not change the PM10 distribution in the VS significantly (Figure 17). The maximum PM10 concentration is slightly increased (from 26.2 to 26.6 μg/m^3) since City Tree #6 is blocking external air entrained through the building facades from the main vortex in the street for this wind direction.

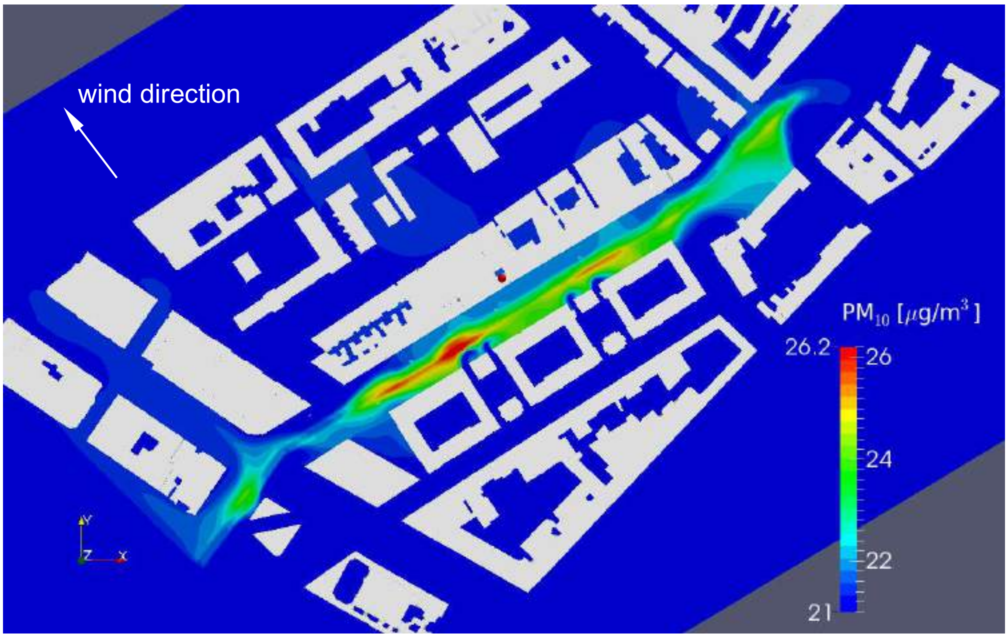


Figure 17: PM 10 concentration distribution at 1.5 m height (with City Trees; City Trees inactive; max 26.6)

When activating the City Trees (ventilation speed 0.5m/s, 19% PM10 removal efficiency), the concentration distribution slightly changes (Figure 19, top).

The maximum concentration increases in the centre of the street since City Tree #6 is blocking the external flow slightly. Close to the building facades, the concentrations are slightly reduced. On the northern side, the City Trees are situated in the downflow side of the street vortex where concentrations are lower. At the southern side, clear wakes of the City Trees are present where the PM10 concentration is reduced to the background level value. The wakes have approximately the width of the City Tree. When located in the middle of the building façade, the effect of the City Trees is maximum (City Tree #2 and #4). Keep in mind that the effect of the City Tree on polluted air with a PM10 concentration of 26 μg/m^3 would reduce the concentration again to background levels behind the City Tree (26*(1-0.19) = 21 μg/m^3). Filtering background air with PM10 background concentrations would lead to a PM10 concentration of 17 μg/m^3

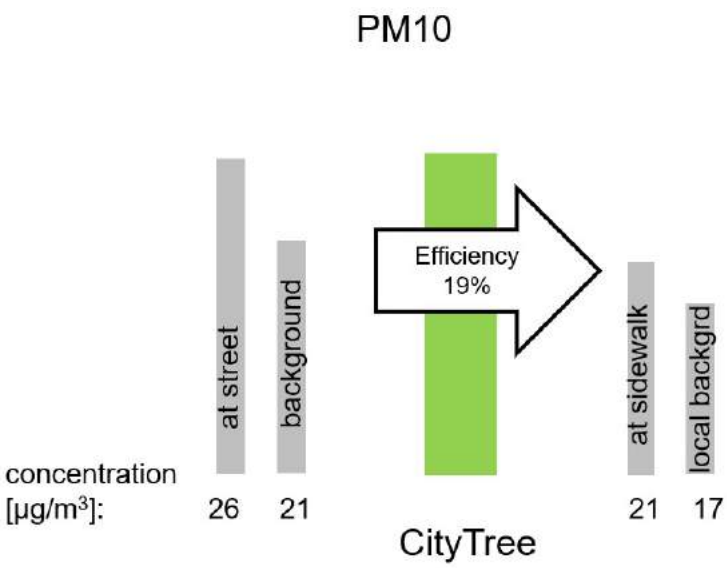


Figure 18: Effect of City Tree on PM10 concentrations at sidewalk

When scaling the concentrations to its full range (Figure 19 bottom) the removal of PM10 concentration below the background level can be seen clearly. In the wakes of the City Trees at the northern side of the VS, the PM10 concentrations reach 17μg/m^3 compared to 21μg/m^3 in the background concentration. The effect is very local (a few meters behind the filter exit of the City Tree).

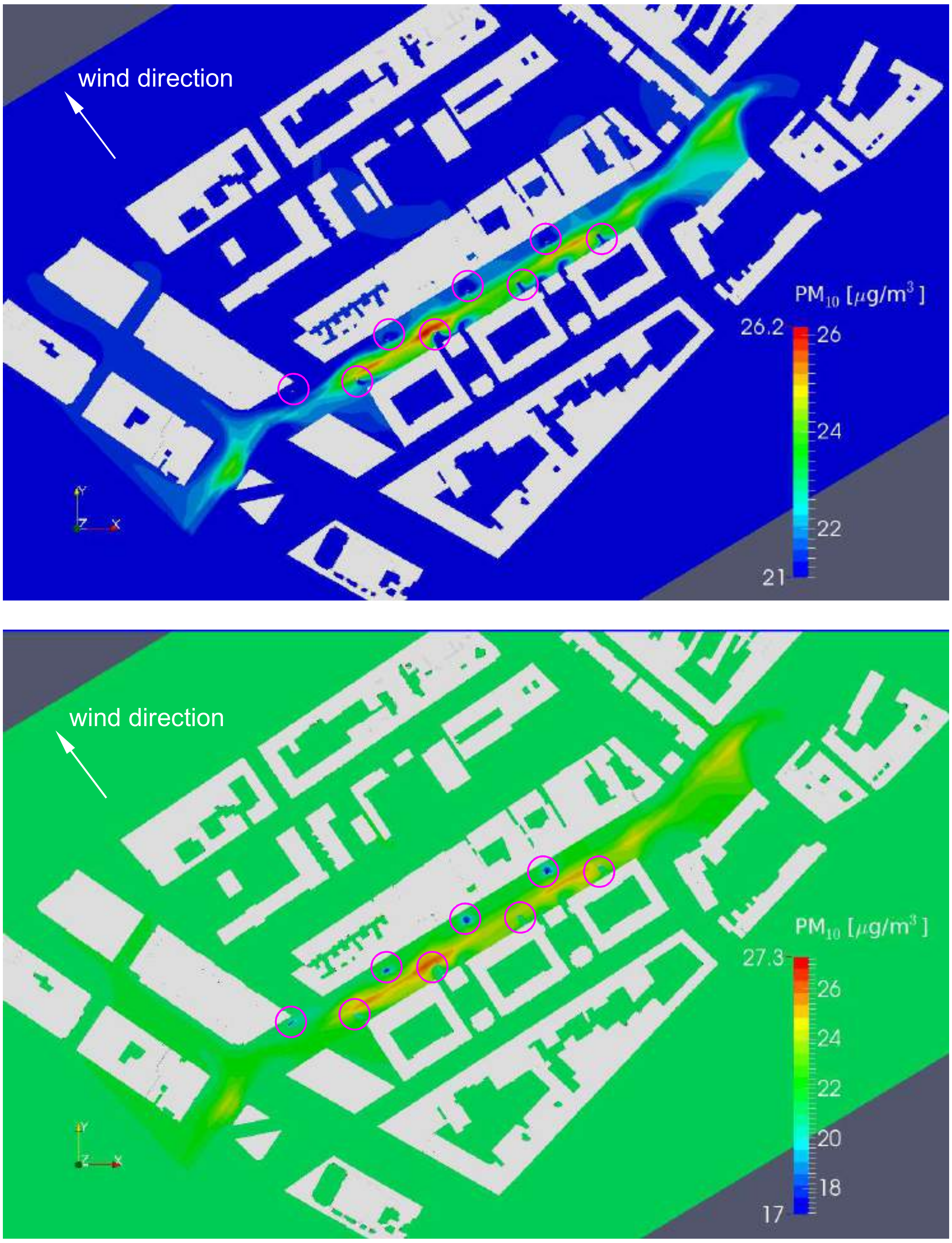


Figure 19: PM10 concentration distribution at 1.5m height with active City Trees (top); Legend scaled to full range (bottom) (SE winds)

The maximum absolute change[5] in PM10 concentration at a height of 1.5m is 4.6μg/m^3 which is achieved in the wake of the southern City Trees #2 and #4 which are placed in the middle of the building facades (Figure 20). On the northern side, the reduction is slightly less. In a large part of the VS the PM10 concentration is reduced by approximately 1 μg/m^3. The maximum local increase in PM10 concentration is 2.2 μg/m^3 and is reached locally on the southern sidewalks. These are areas where the concentrations where low due to entrained external air. Now, the City Trees influence the entrainment or the local flow separations at the facades such that more emissions are reaching this area.

[5] Negative values indicate improvement of air quality.

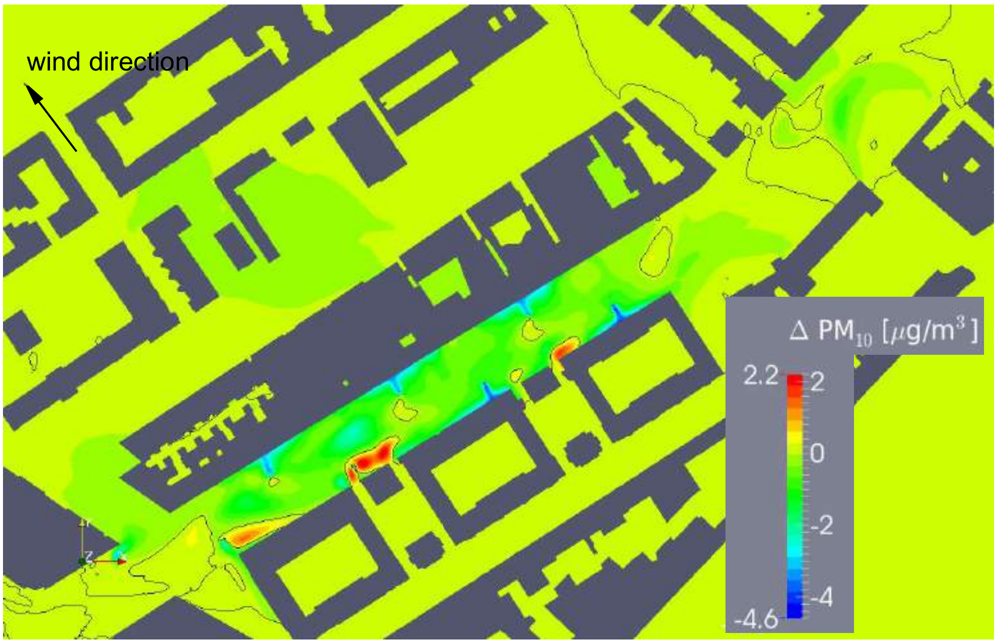


Figure 20: Difference of PM10 concentration due to City Trees. Negative values indicate an improvement of air quality. (SE winds)

3.2 Wind direction South-West: wind direction aligned with street

For the second wind direction investigated (wind from south west) the main wind direction is aligned with the VS. Due to buildings upstream the VS on one side and some low-rising structures on the other side the airflow is disturbed and is therefore entering the VS disturbed at lower speed (

Figure 21). Inside the VS, between the buildings the flow is nearly aligned with the street direction. A very long stretched vortex is present in the VS where the flow close to the street is directed to the northern building facades.

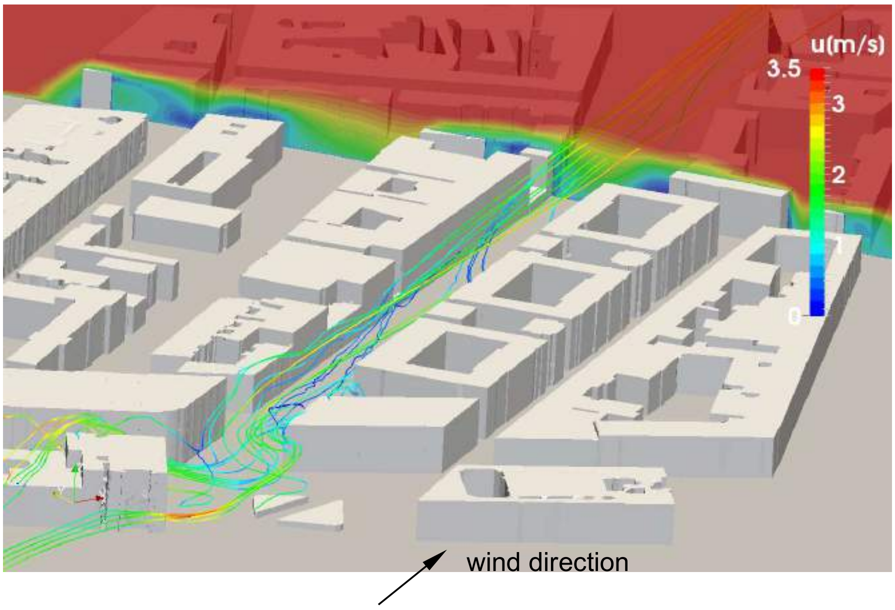


Figure 21: Flow topology in VS (wind south-west) shown by velocity on streamlines and plane

Comparable to the previous results the presence of the City Trees does not influence the global flow topology significantly (compare

Figure 21 and Figure 22).

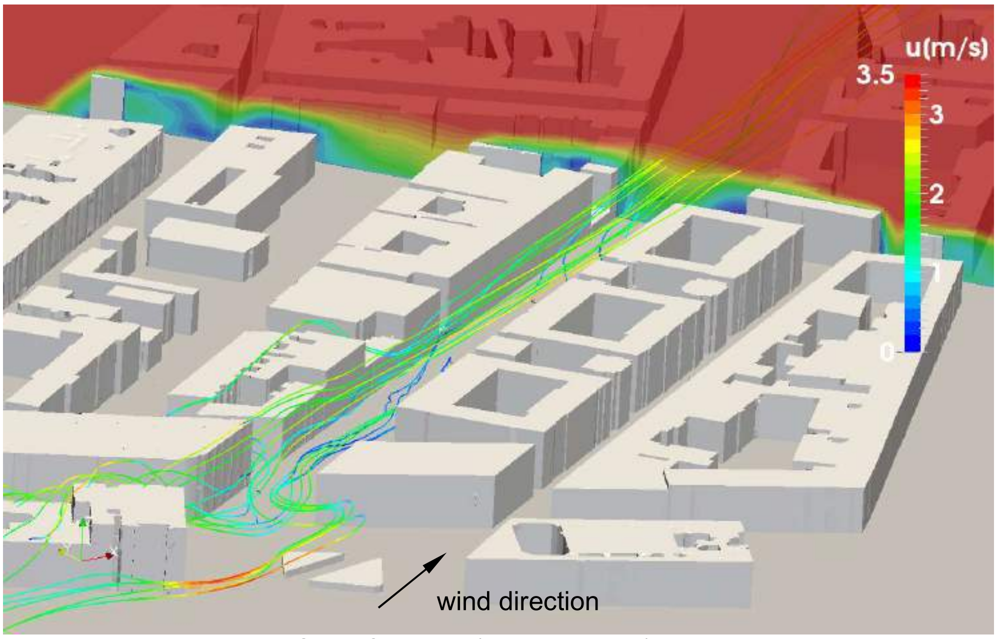


Figure 22: Flow topology in VS with City Trees (wind south-west) shown by velocity on streamlines and plane

Again, three PM10 dispersion calculations were performed: the reference situation without City Trees, the situation with inactive City Trees and one with active City Trees.
Overall, the maximum PM10 concentrations are lower compared to the previous wind condition since the wind speed is higher and the flow is aligned with the street which enhances mixing. In addition, the PM10 background concentration is lower (15 µg/m³). The additional PM10 concentration due to the traffic (with identical traffic emissions) is therefore only 2.36 µg/m³ (Figure 23). The inactive City Trees again do not change the PM10 distribution significantly (not further shown here). The concentration calculated is marginally lower than observed in the van Diemenstraat with these conditions.

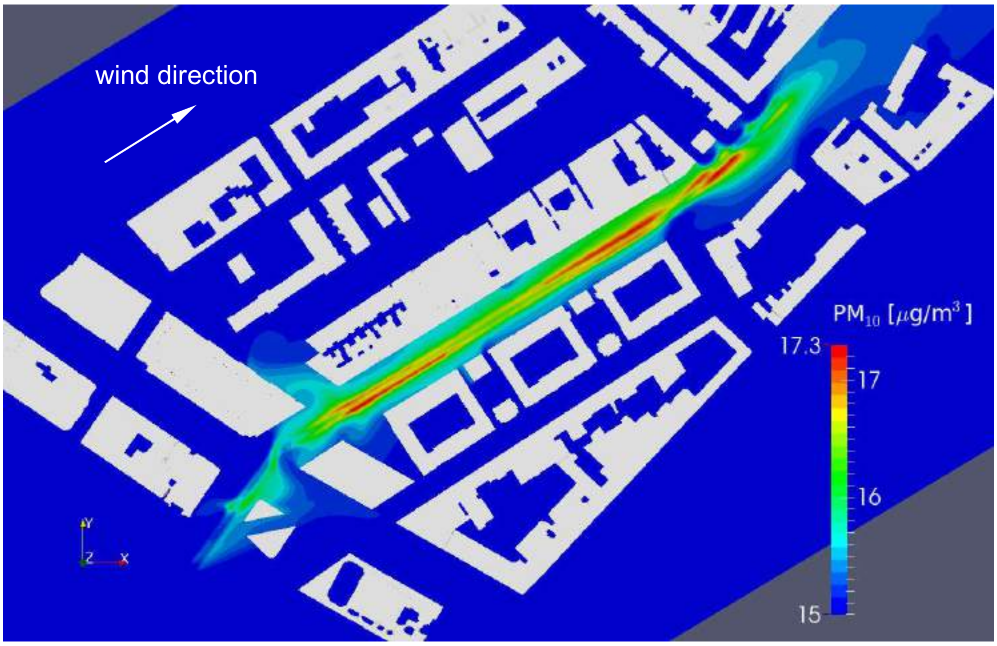


Figure 23: PM 10 concentration at 1.5m height (no City Trees)

With active City Trees, plumes behind the City Trees with concentrations at approximately background level can be seen (Figure 24, top). In the sidewalk area at the Northern facades at the beginning of the street relatively low concentrations are present which rise further downstream. Close to the southern facades, the opposite takes place: concentrations are decreasing and the City Trees have more impact. This is due to the large longitudinal vortex in the street which redirects the emissions from the center of the street to the northern facades.
Due to the interaction of the City Trees (#7 and #8) with the air entering the street partial blockage is taking place which increases the maximum concentrations in that area (middle of the street) to 17.5 µg/m^3. The lowest local PM10 concentration is 12.5 µg/m^3 (behind City Tree #8) which indicates that this City Tree is mainly cleaning the background concentration (Figure 24, top and bottom).

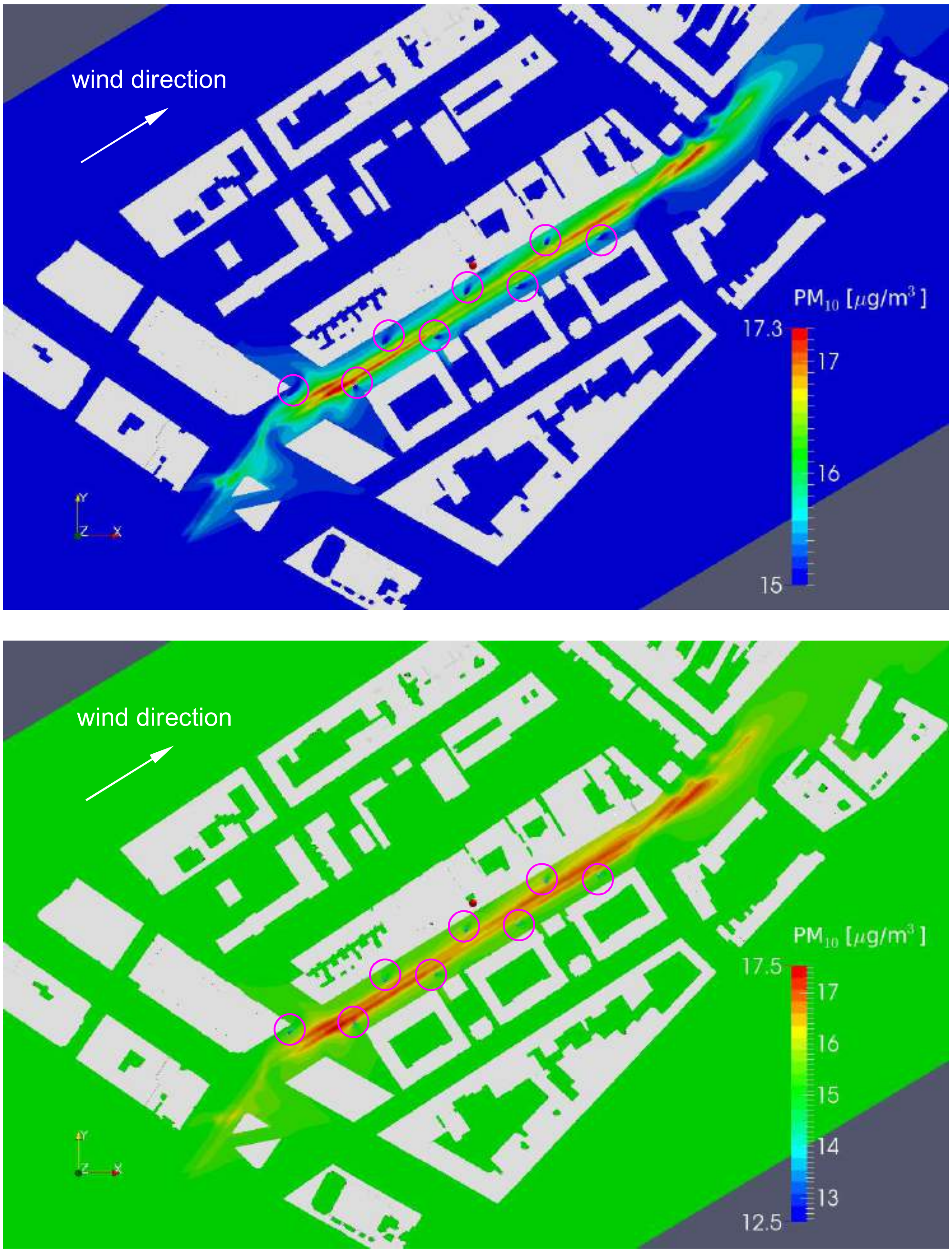


Figure 24: PM10 concentration distribution at 1.5m height with active City Trees (top); Legend scaled to full range (bottom)

The maximum absolute change[6] in PM10 concentration at a height of 1.5 m is 2.5 µg/m³ just behind the City Tree (#7 for example) which is achieved in the wake all City Trees (Figure 25). Through the street the reductions are similar on both sides with typical values of 0.1 to 0.2 µg/m³ There is a small increase in concentration in the beginning of the street due to specific air flows caused by the City Trees.

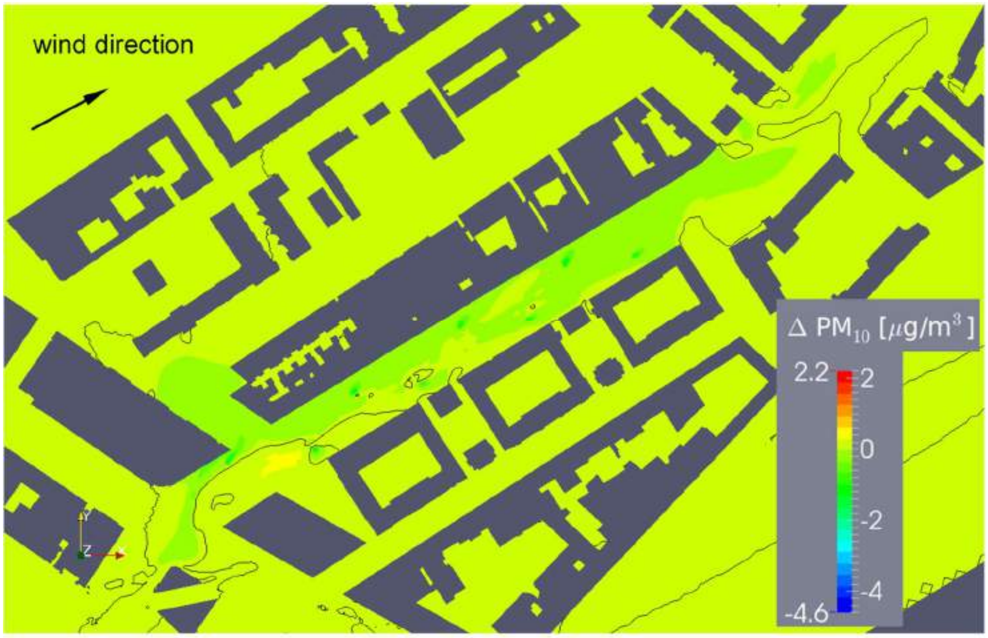


Figure 25: Difference of PM10 concentration at 1.5 m due to City Trees

3.3 Wind direction South: wind direction 45º with respect to street

For the wind direction 45º with respect to the street (approximately wind from south) a simulation was performed in order to get a representative overview of all relevant flow conditions in the Valkenburgerstraat.
From the flow topologies without (and also including the City Trees) it can be seen that also for this wind direction a large rotating vortex is building up in the Valkenburgerstraat (Figure 26 and Figure 27). The City Trees do not influence the flow pattern significantly.

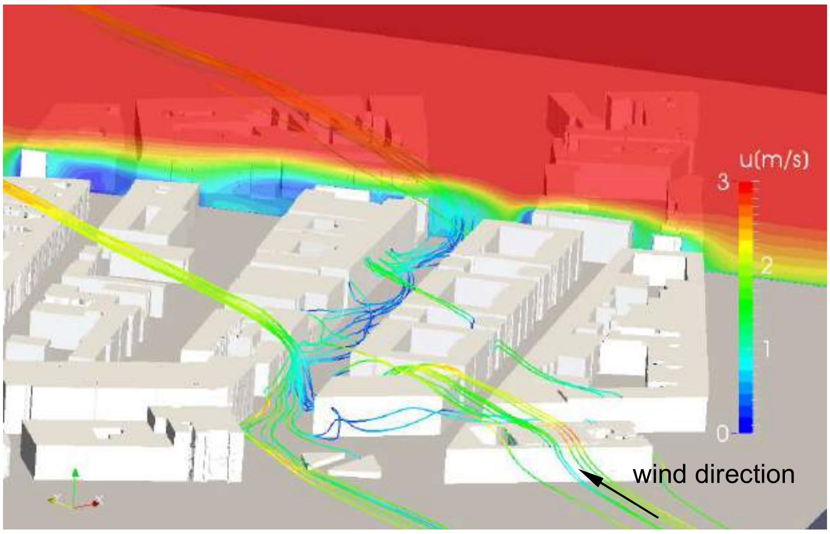


Figure 26: Flow topology in VS (wind south-west) shown by velocity on streamlines and plane (no City Trees)

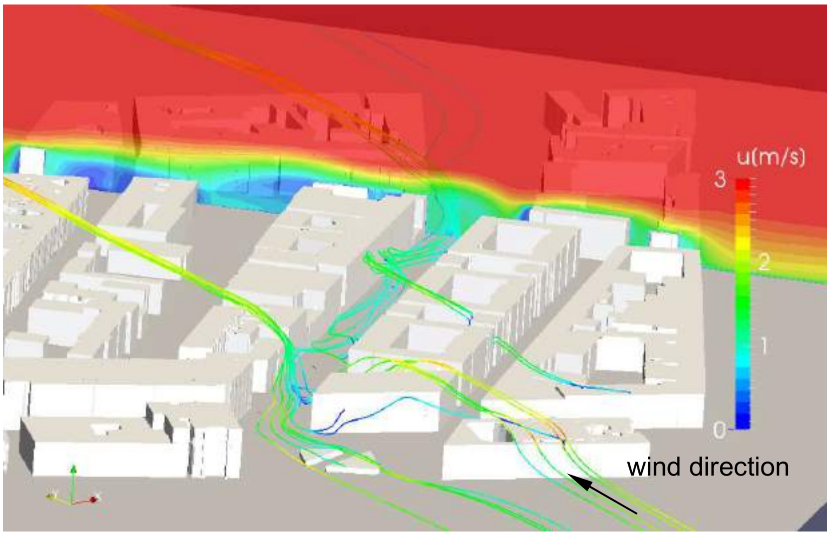


Figure 27: Flow topology in VS (wind south-west) shown by velocity on streamlines and plane (no City Trees)

The PM10 concentrations without City Trees (Figure 28) and with City Trees (Figure 29) are higher close to the southern facades due to the large vortex in the street whereas on the northern side fresh air is entrained. The average reduction of PM10 is approximately 0.1-0.2 µg/m³ at 1.5 m height (Figure 30).

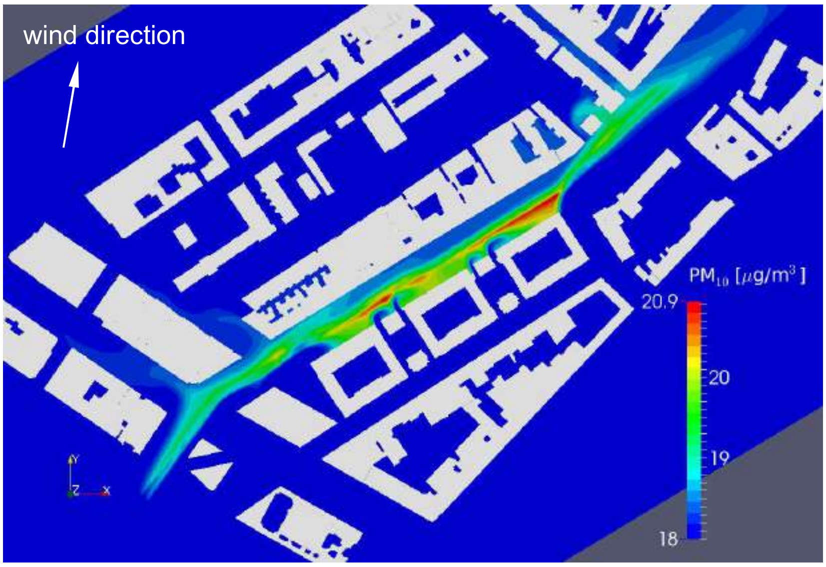


Figure 28: PM 10 concentration at 1.5 m height (no City Trees)

Figure 29: PM10 concentration at 1.5 m height (with City Trees)

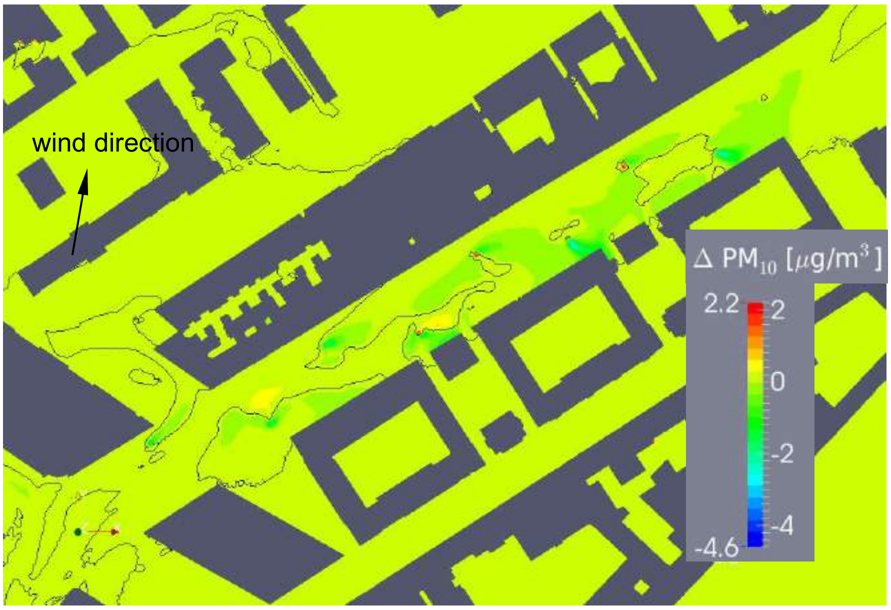


Figure 30: Difference of PM10 concentration at 1.5 m due to City Trees

3.4 Analysis of NO_2 concentration for three wind directions

For all three wind directions NO_2 distribution calculations were performed with the given emissions of NO_2 and NO. As described earlier the NO emissions are transformed by the presence of ozone into additional NO_2. The principal distributions (without the City Trees) are comparable to the PM10 distributions whereas the range is different. The maximum concentrations are approximately a factor of 5 higher compared with the PM10 distributions.

The effect of the City Tree on polluted air with a NO_2 is strongly different from the one on PM10 since the concentration levels and filter efficiencies are different. NO_2 concentration of 70 µg/m³ would be reduced by the City Trees to a concentration level of (70*(1-0.05)=67µg/m³). This concentration will then be present on the sidewalk which means a significant increase at the sidewalk. Filtering background air with NO_2 background concentrations (17µg/m³) would lead to a small decrease in NO2 concentration to 16µg/m³, compare also Figure 31.

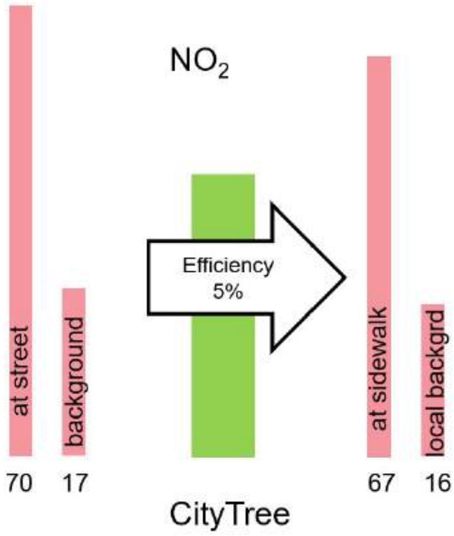


Figure 31: Effect of City Tree on NO_2 concentrations at sidewalk

Although the global distributions are not changed significantly (Figure 32 and Figure 33) due to the City Trees, the local distributions change up to +41/-35µg/m³ and large areas are in the range of +/-10µg/m³ (Figure 34). Especially in regions where the City Trees prevent the entrainment of external air (at the entrance of the street, south side) concentrations are increasing.

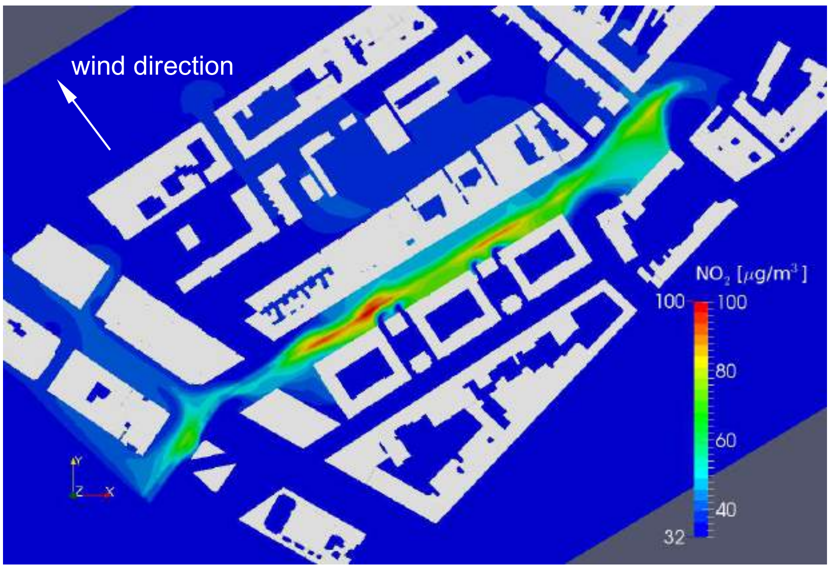


Figure 32: Wind south east, NO_2 concentration at 1.5m height (no City Trees)

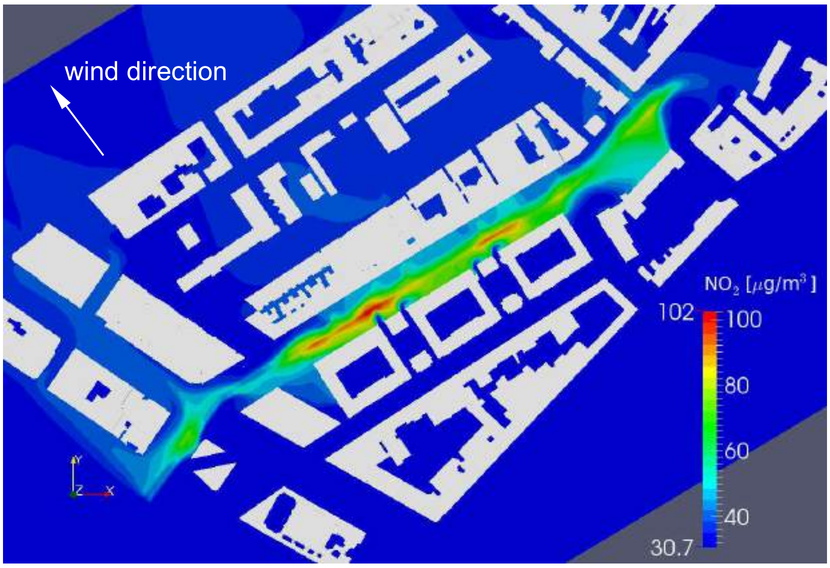


Figure 33: Wind south east, NO_2 concentration at 1.5m height (with City Trees)

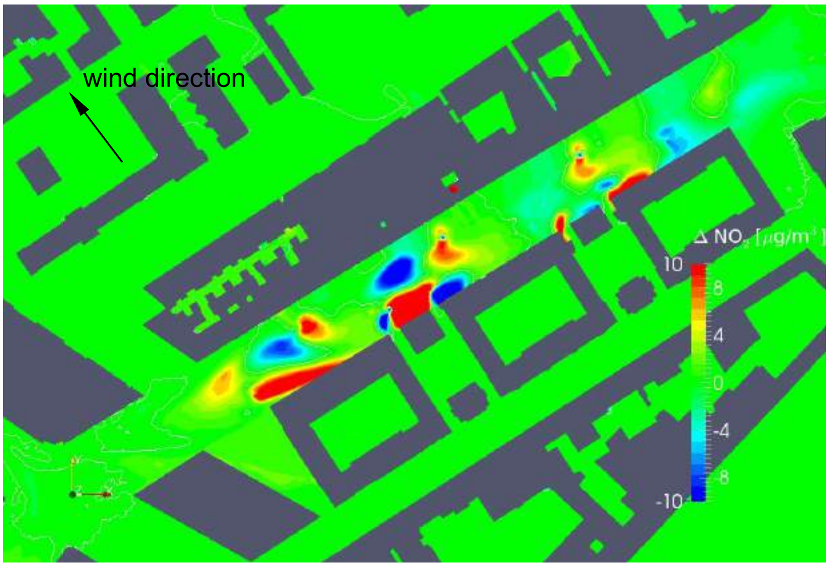


Figure 34: Wind south east, difference of NO_2 concentration at 1.5 m height

For south-western wind, the largest changes in the NO2 concentrations due to the City Trees are present at the entrance of the street (Figure 35, Figure 36, Figure 37). Here, the City Tree 8 is located in the wake of the building, therefore the air is entrained multiple times through the City Tree and the effect is higher than anywhere else. In contrary, City Tree 7 slightly prevents the entrainment of external air into the street, therefore the NO_2 concentration there increase. Overall, the changes are relatively small in the rest of the street. Maximum changes are in the range of +6/-8µg/m^3 .

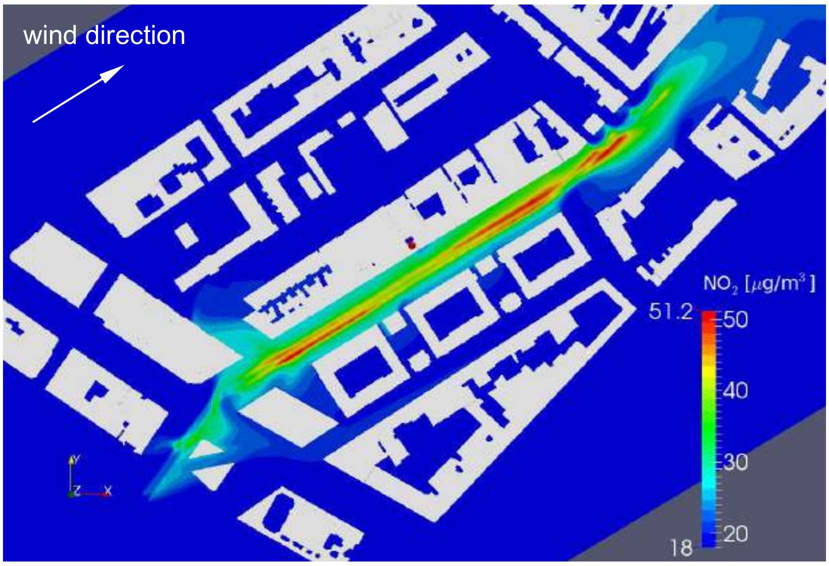


Figure 35: Wind south west, NO_2 concentration at 1.5m height (no City Trees)

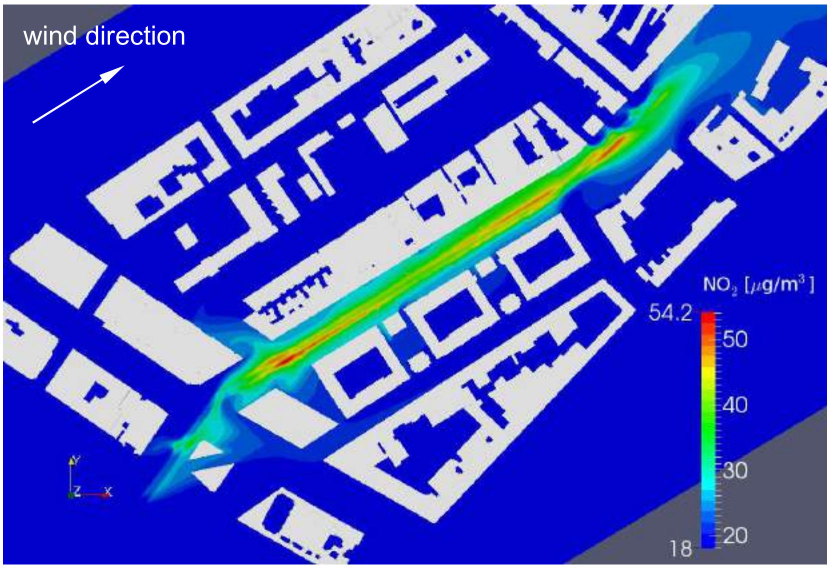


Figure 36: Wind south west, NO_2 concentration at 1.5m height (with City Trees)

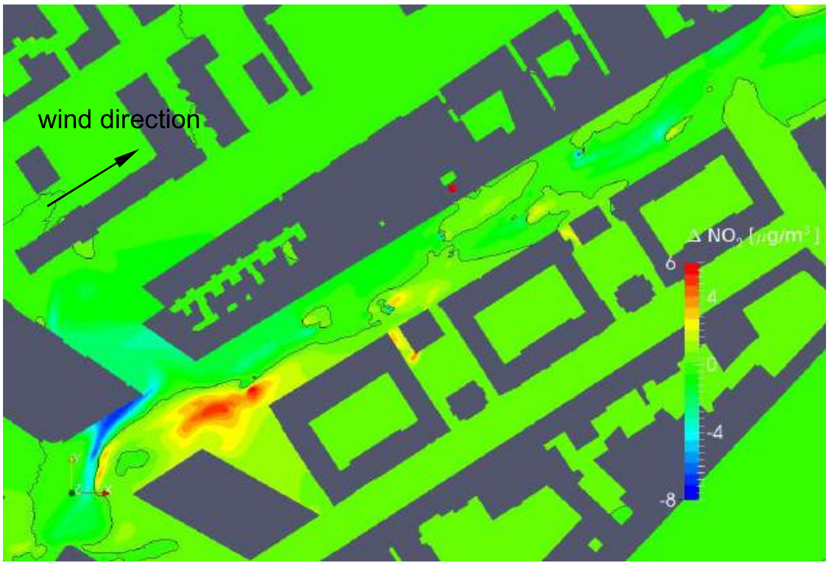


Figure 37: Wind south west, difference NO_2 concentration at 1.5m height

For the southern wind direction, changes in the NO2 concentrations are rather low due to the City Trees (Figure 38, Figure 39). The maximum difference is approximately +20/-15 μg/m³ (Figure 40)

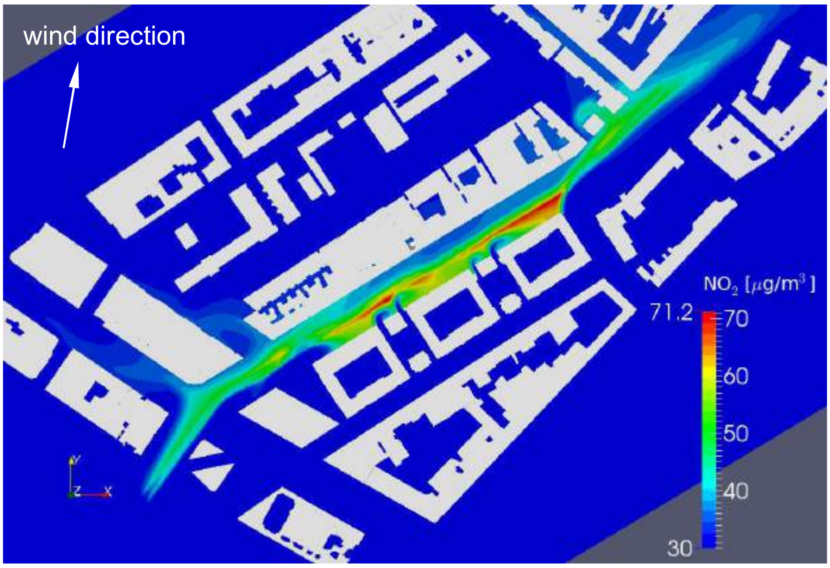


Figure 38: Wind south, NO_2 concentration at 1.5m height (no City Trees)

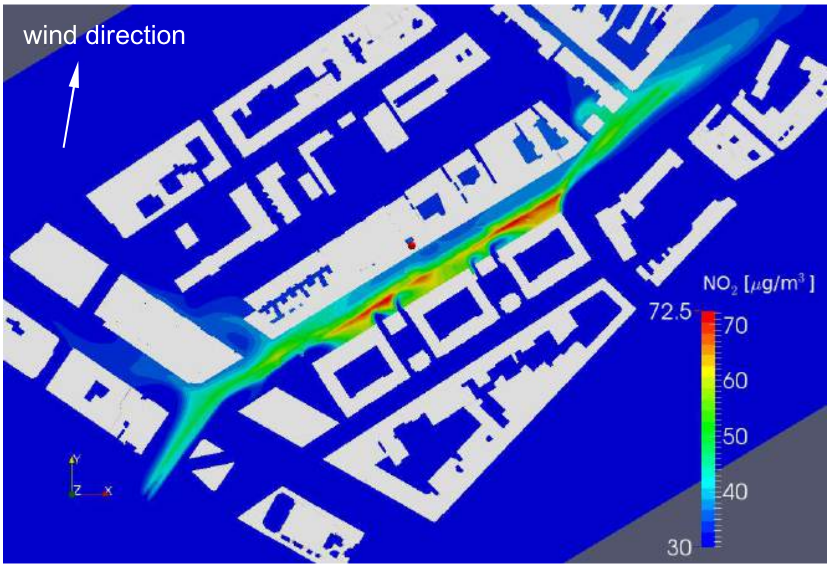


Figure 39: Wind south, NO_2 concentration at 1.5m height (with City Trees)

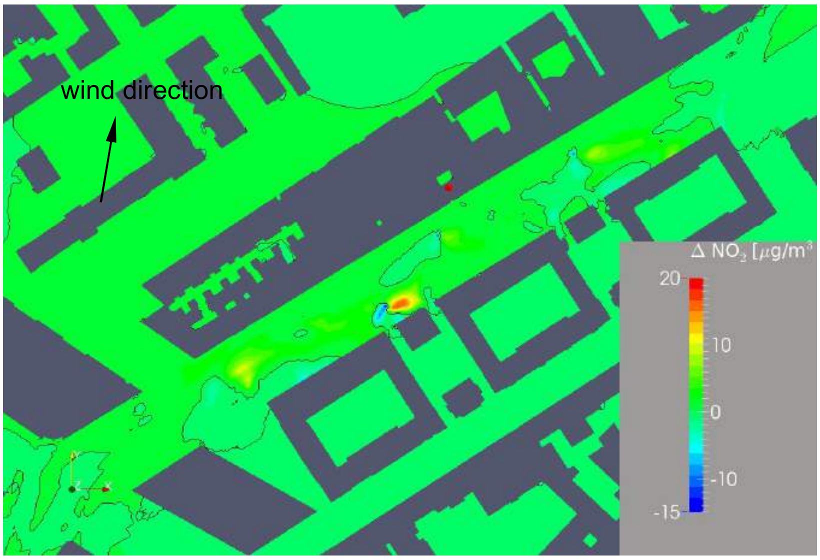


Figure 40: Wind south, difference NO_2 concentration at 1.5m height

3.5 Comparison of concentrations at facades

To quantify the effectiveness of the City Trees in the VS for the three investigated wind conditions the PM10 and NO_2 data at the building facades in the VS were analysed.

3.5.1 Comparison of building façade distributions

For all three wind directions the concentrations at the facades are given separately for the façade on the North and the South side of the streets

The figures include a comparison of the reference case without City Trees (bottom of figure) and the situation with active City Trees (top of figure) (Figure 41 - Figure 44) Due to the entrainment of air from the surroundings at the northern facades (south eastern wind, street canyon vortex flow), the City Trees do not show a strong influence there since the concentrations are already low (Figure 41). A larger impact can be seen on the southern facades (Figure 42), where the City Trees blow the cleaner air at the façade. Due to the flow direction of the City Trees which is aligned with the large street canyon vortex, the concentrations are reduces over relatively large areas in the wake of the City Trees. Concentration reductions also at the top level of the buildings are present. The City Trees which are placed in the middle of building facades (undisturbed from flow entering the street canyon in between buildings) like City Tree #1 and #3 (but also #2 and #6 at the northern facades, compare Figure 41) show the highest PM10 reductions.

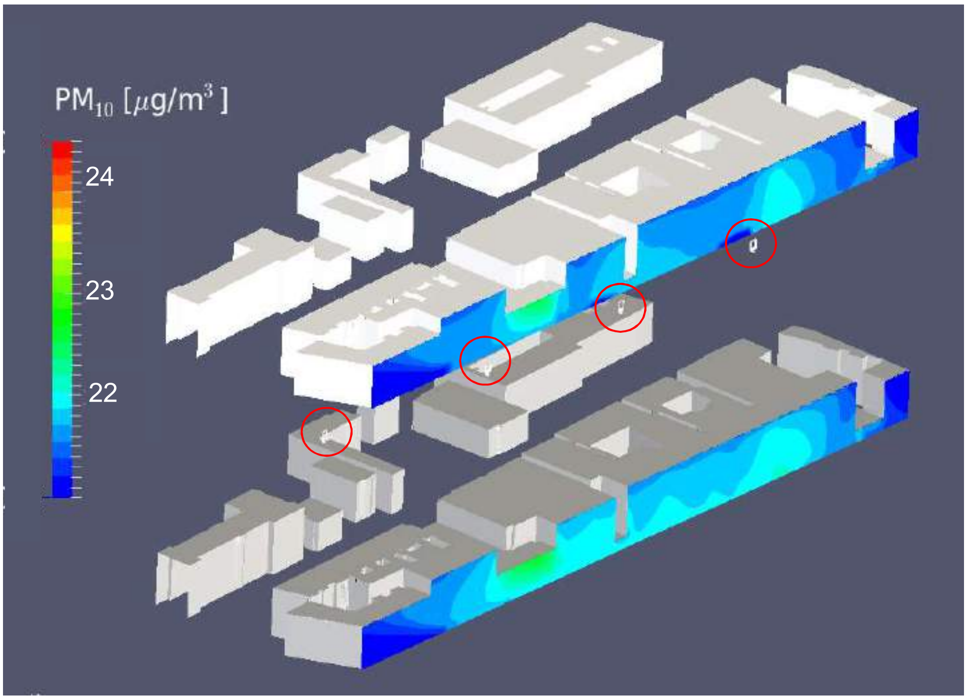


Figure 41: South eastern wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

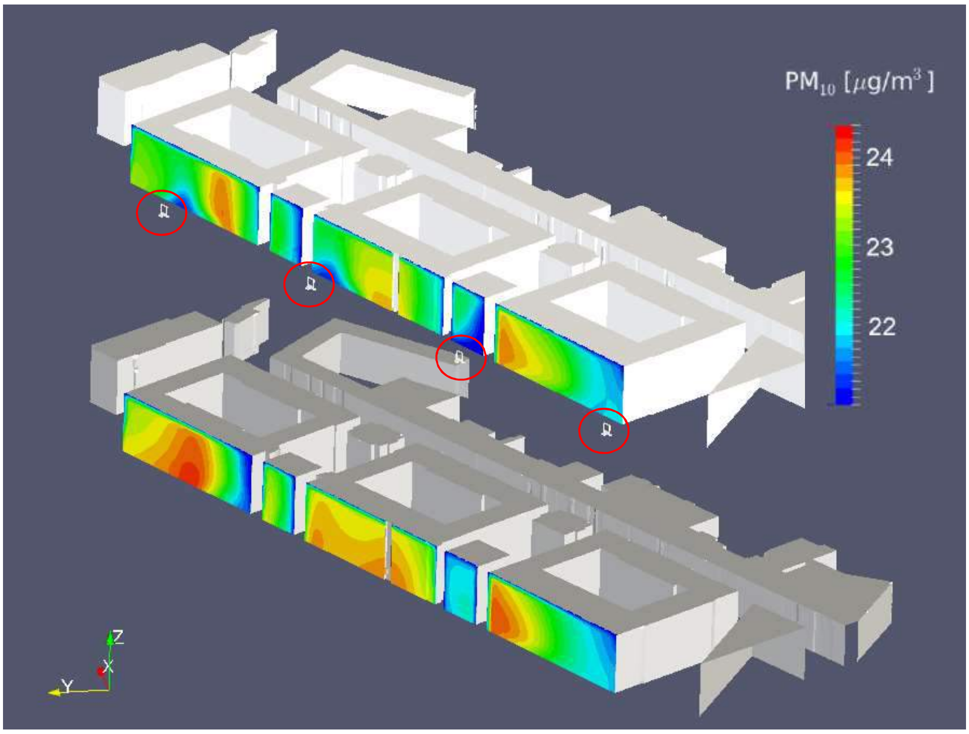


Figure 42: South eastern wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

For the wind direction from south-west (main wind direction aligned with VS) the PM10 distributions on the northern and southern building facades are more uniform as expected (Figure 43 and Figure 44). Due to the longitudinal vortex in the street as explained before the increasing concentrations at the northern facades and the decreasing concentrations at the southern facades can be seen. The absolute reduction of PM10 level is lower compared with south-eastern wind but also here the reduction of PM10 level at the facades is present.

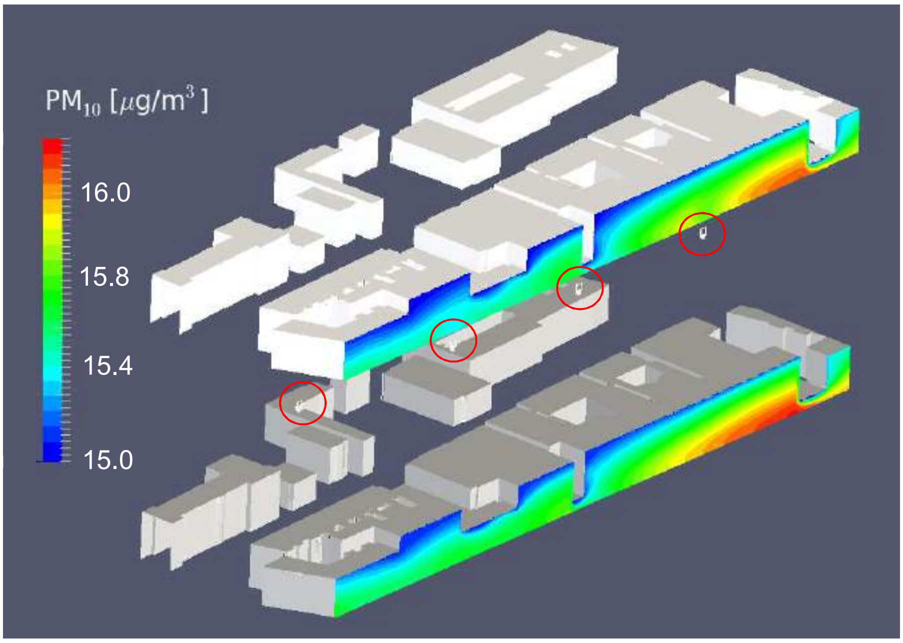


Figure 43: South western wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

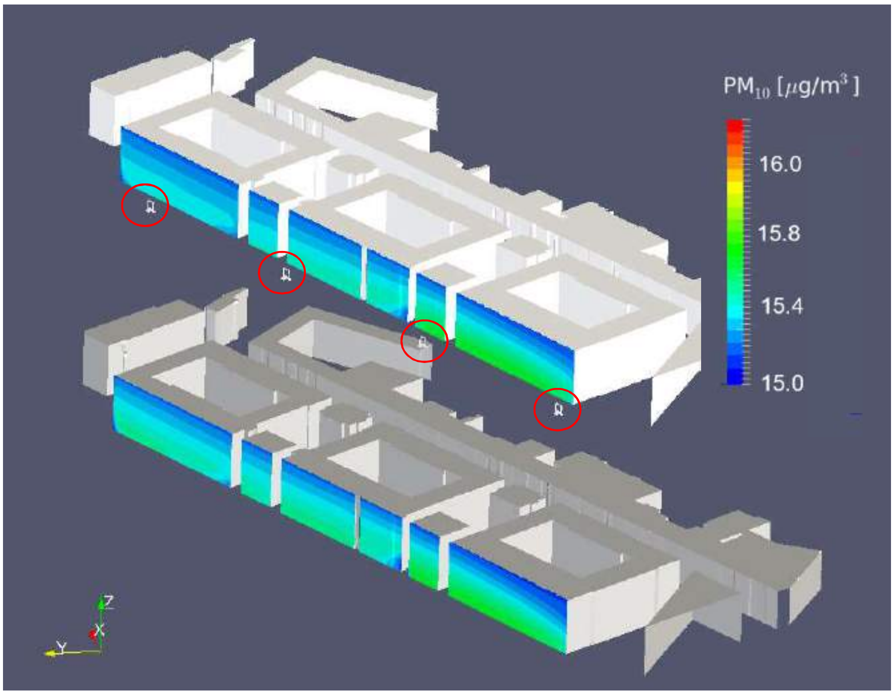


Figure 44: South western wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

For the wind direction from south, PM10 reductions are almost comparable to the results of the south-west wind direction.

Due to the presence of the large vortex in the street, the effects of the City Trees can mainly be seen downstream of the City Trees. The effect on the facades also here is rather limited since there is a significant flow component along the street due to the external wind.

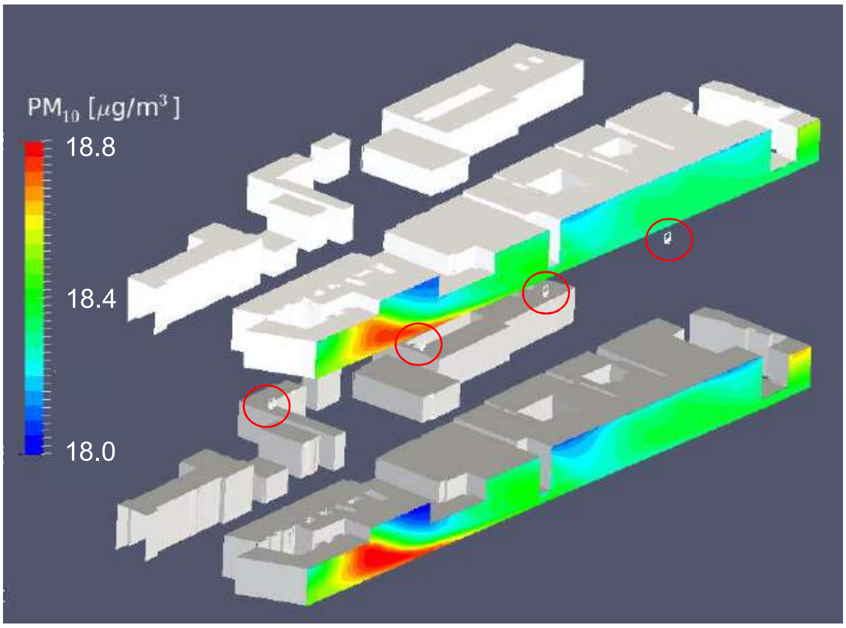


Figure 45: South wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

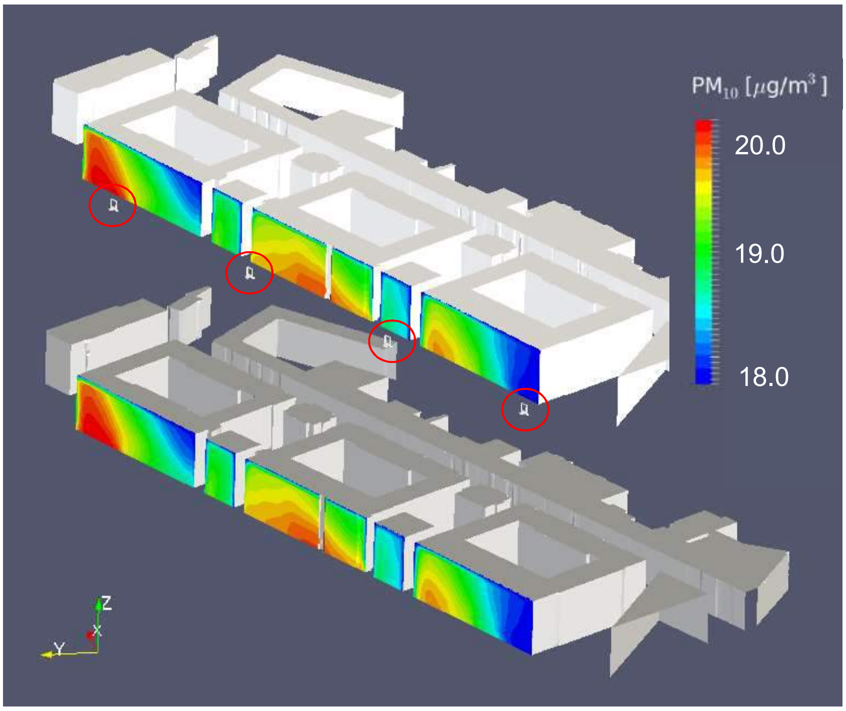


Figure 46: South wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

For NO_2, the local effects of the City Trees are much larger than for PM10 due to the higher absolute levels (Figure 47-Figure 52). Especially on the facades which show higher concentrations (since the emissions are transported by the large vortex in the street) the City Trees can have a large impact on the local concentrations.

Local increases up to 30 µg/m³ (wind south-west, Figure 48) but also locally decreases (5-10 µg/m³) are present. These changes are not always based on the efficiency of the City Trees but also on local changes of the main flow direction and hereby locally enhanced or reduced entrainment of external air.
Due to the efficiency of the City Trees with respect to NO2 removal of only 5% the overall reduction is rather low, especially for the facades with external air entrainment or a relevant wind component along the street. Here, the NO_2 concentrations as a fact are lower and the impact of the City Trees on the global NO_2 level is therefore rather limited.

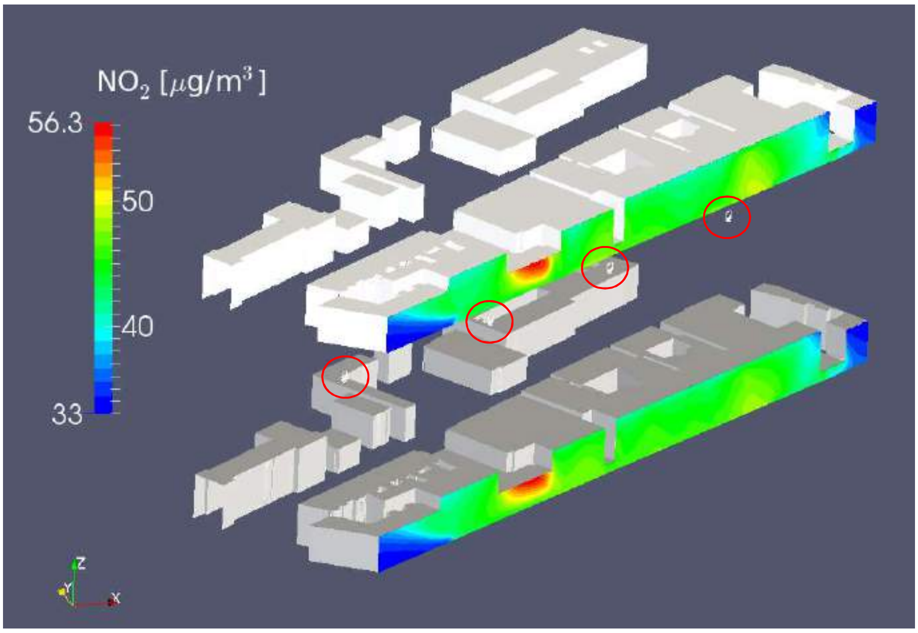


Figure 47: South-east wind NO_2 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

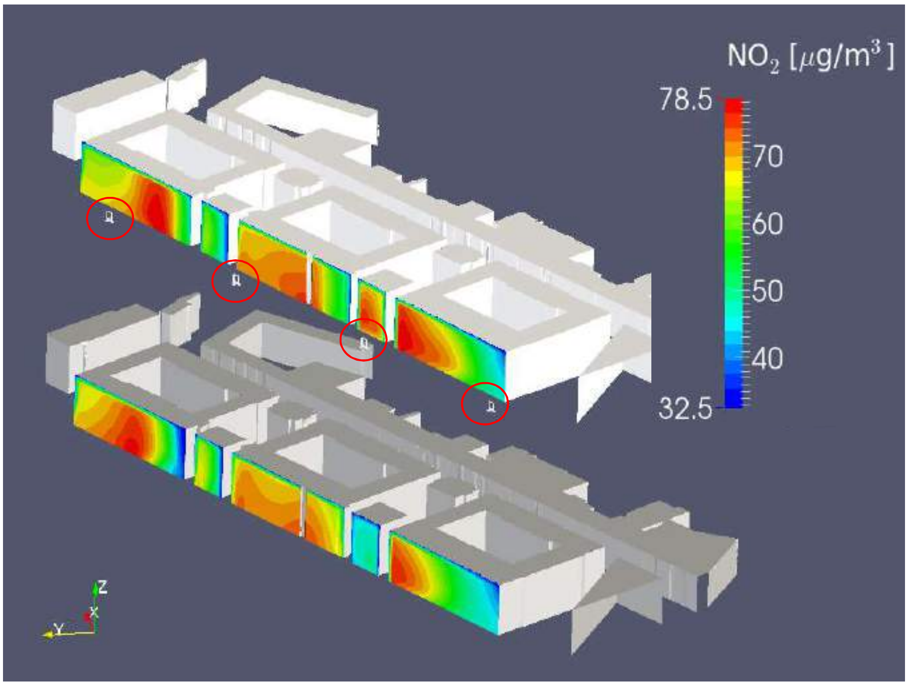


Figure 48: South-east wind NO_2 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

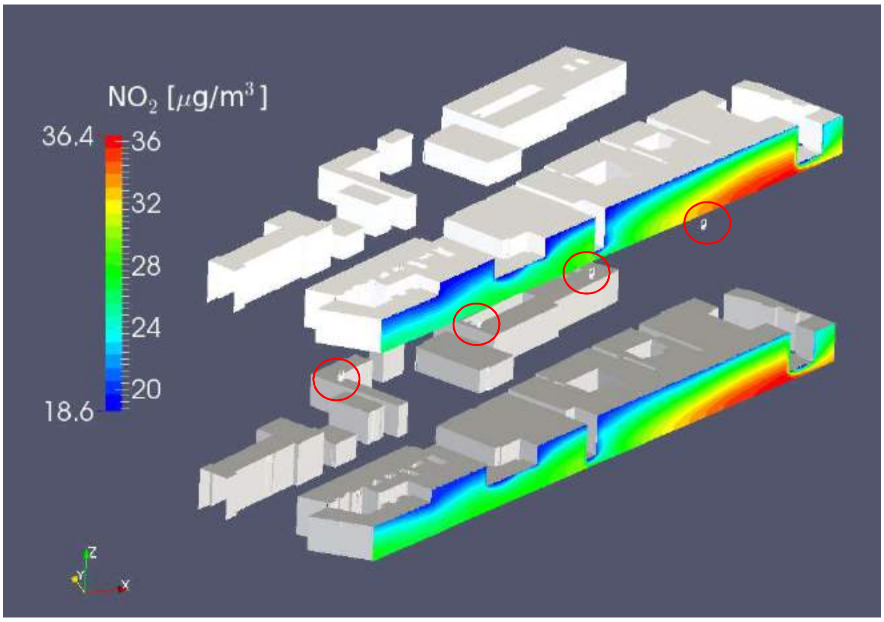


Figure 49: South-west wind NO_2 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

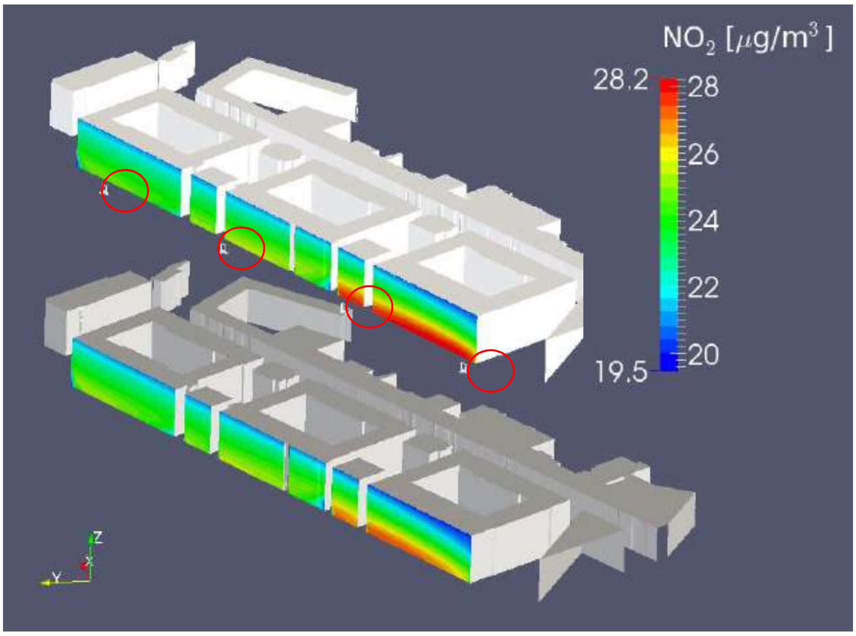


Figure 50: South-west wind NO_2 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

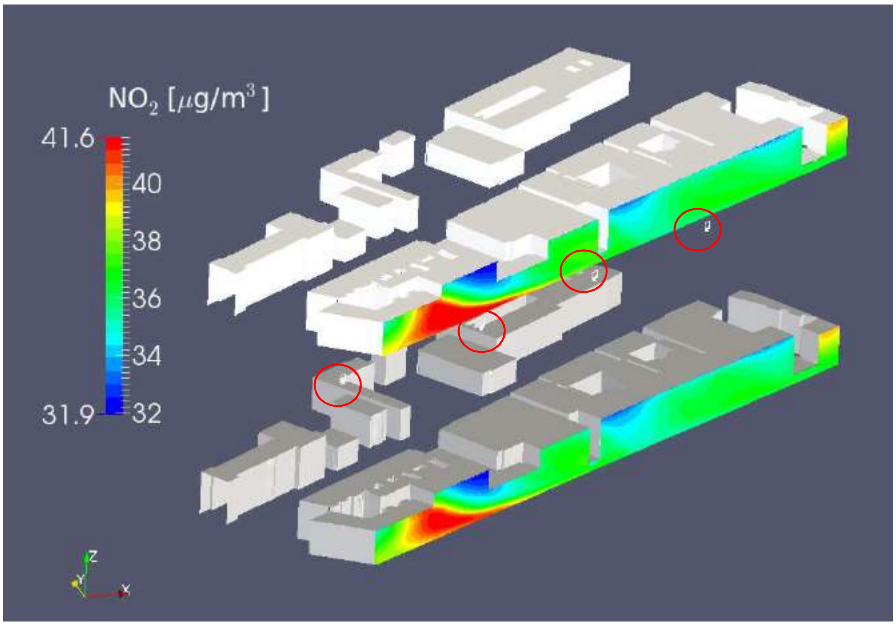


Figure 51: South wind NO_2 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

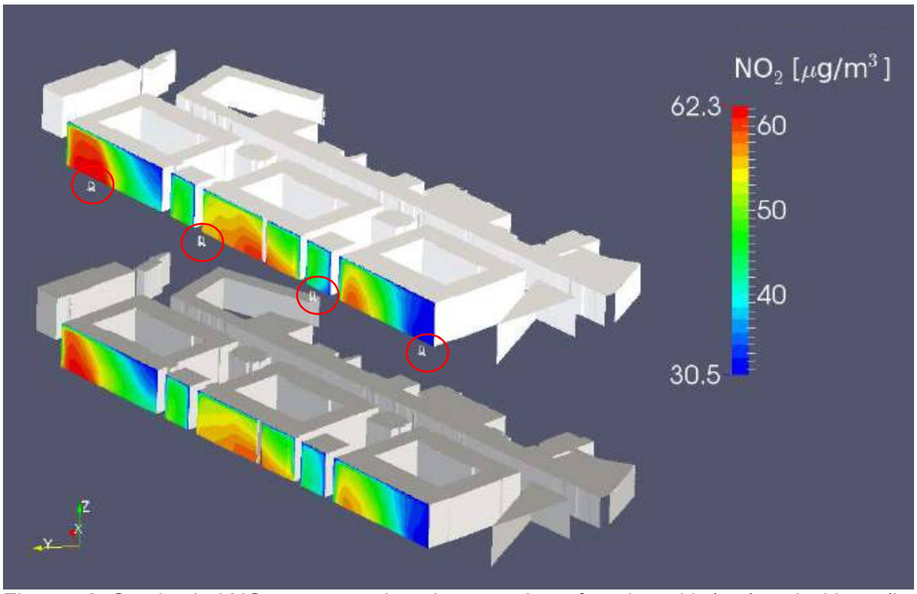


Figure 52: South wind NO_2 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

3.5.2 *Local comparison of concentrations at ground level, 2nd and 5th floor*

A comparison of the data at ground level, 2nd and 5th floor (1.8 m height, 9 m and 19 m) is performed to show the effectiveness of the City Trees at the different levels. For all wind conditions, concentration reduction are calculated on all three levels (Figure 53, Figure 55 and Figure 56-Figure 58). Locally, the reduction is reduced with height. Best performance is achieved for south-eastern wind (street canyon vortex flow) at the southern facades (Figure 53). Large reductions are present at City Trees which are places in the middle of building facade; here significant reductions (1.5 µg/m^3) are predicted also at the 5th floor. At the northern facades, the effect is mainly local but also globally the concentrations are slightly reduced (ca 0.15µg/m^3) also at higher levels (Figure 55).

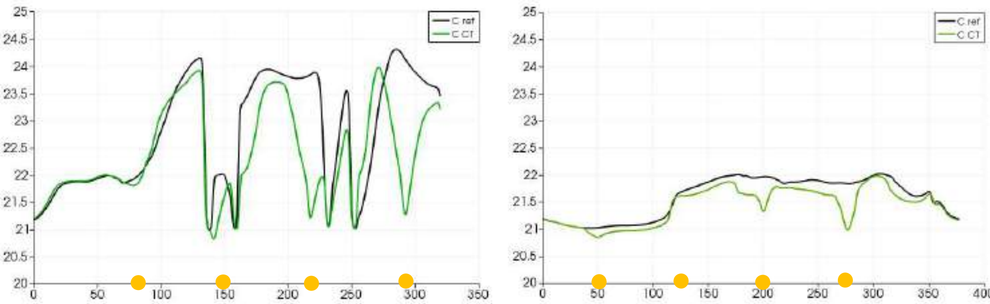


Figure 53: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8 m (wind south-east)

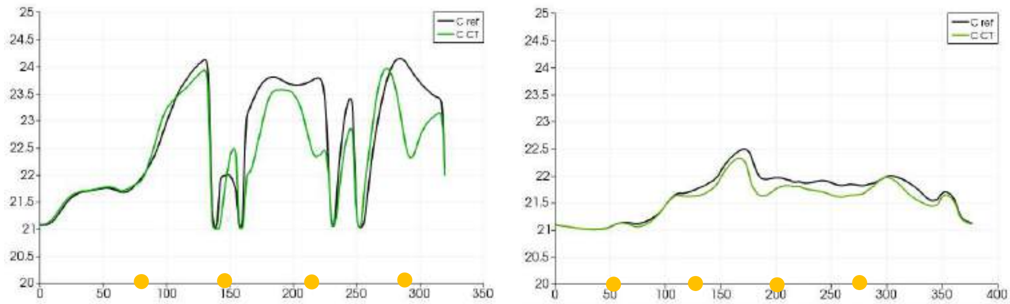


Figure 54: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9 m (wind south-east)

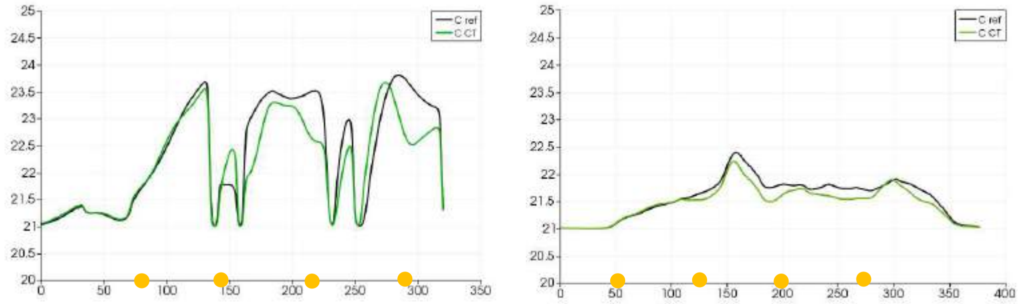


Figure 55: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south-east)

For south-western wind (flow aligned with VS) the largest effect of the City Trees is present at the northern facades at ground level (Figure 56). As explained earlier the traffic emission are entrained in a large longitudinal vortex which leads to increasing concentrations at the northern facades. Here, the concentration reduction is relatively uniform along the facades.

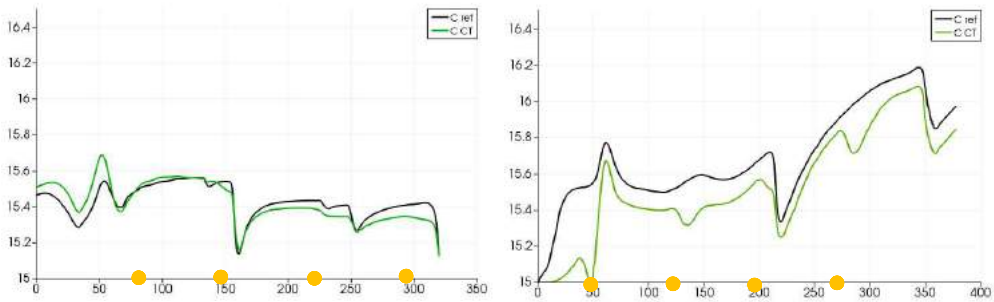


Figure 56: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8m (wind south-west)

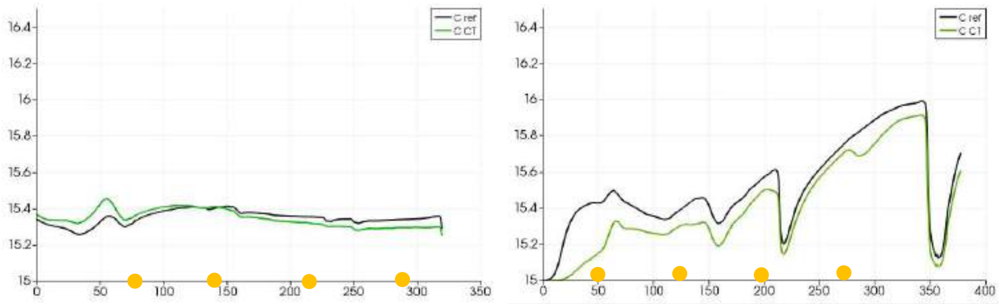


Figure 57: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9m (wind south-west)

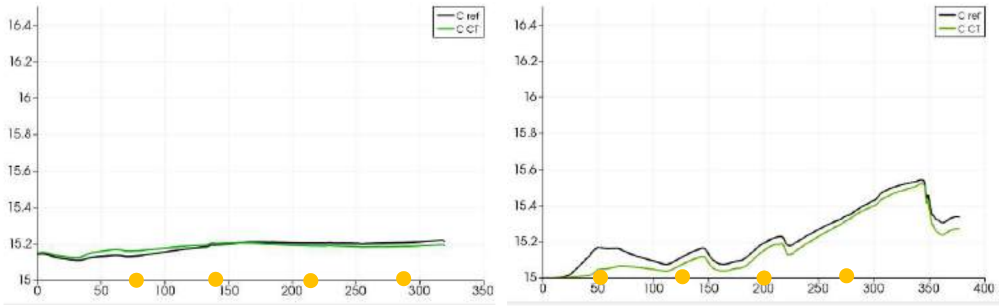


Figure 58: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south-west)

For southerly wind, the PM10 reduction along the facades is also mainly limited to the southern facades (Figure 59-Figure 61). Here, the local reductions reach locally 1.5 µg/m^3, whereas the averaged overall reduction is limited. With height, the PM10 reduction decreases again comparable to the other cases. On the northern facades, the City Trees hardly influence the concentrations distribution on the facades.

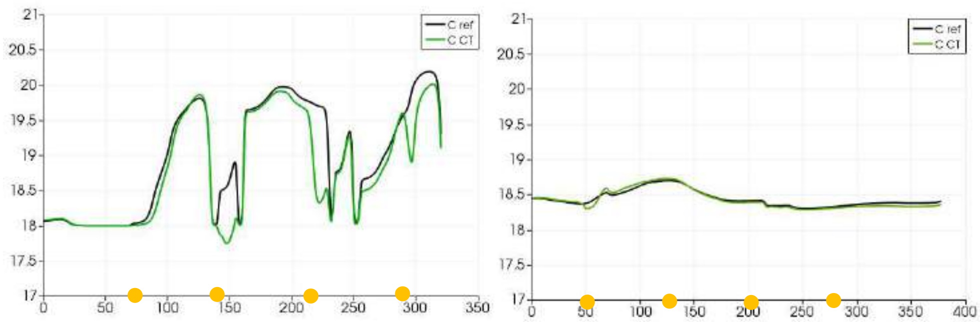


Figure 59: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8m (wind south)

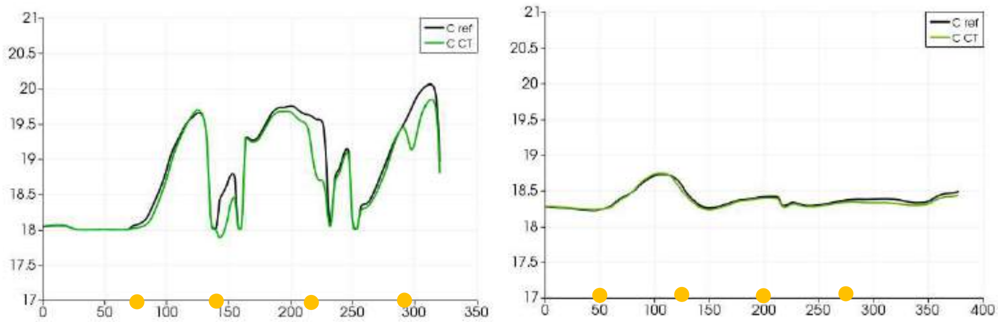


Figure 60: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9 m (wind south)

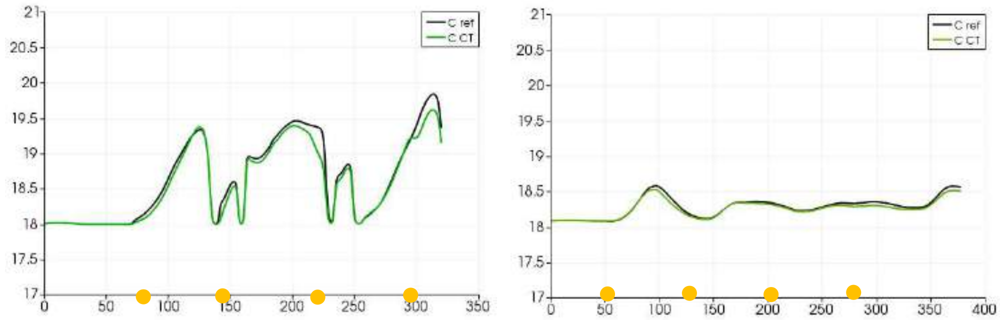


Figure 61: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south)

For NO_2, the local effects of the City Trees show much higher changes in the concentrations since the maximum NO_2 values are much higher compared to PM10 but also the difference with the background values are higher for NO_2. Therefore, maximum increases up to 30 µg/m^3 and increases of approximately 5 µg/m^3 over large facade areas are present at ground floor level with wind from south east (Figure 62, Figure 63). For this case, the local increases are present up to the upper floors (Figure 64). Along the facades, the concentrations are rather increased than decreased.

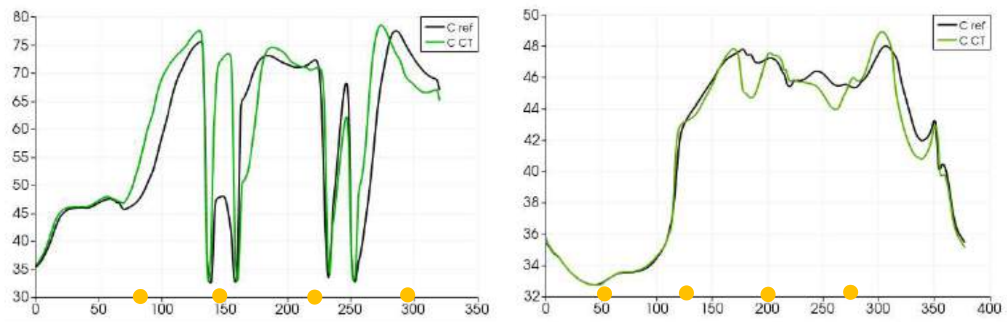


Figure 62: Ground floor NO_2 concentration along southern (left) and northern (right) facades at z=1.8m (wind south-east)

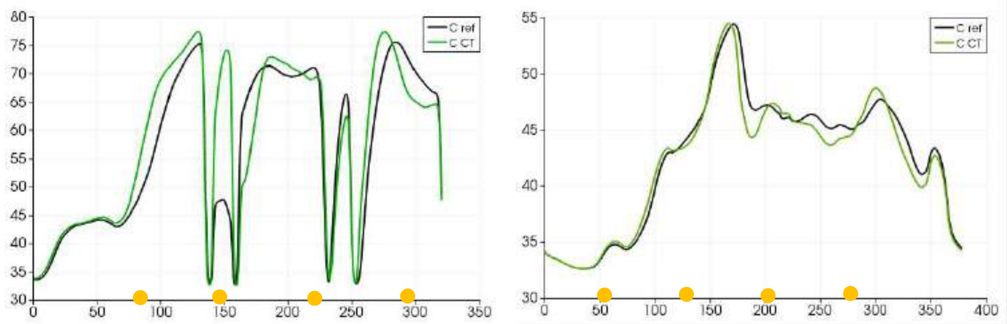


Figure 63: 2nd floor NO_2 concentration along southern (left) and northern (right) facades at z=9m (wind south-east)

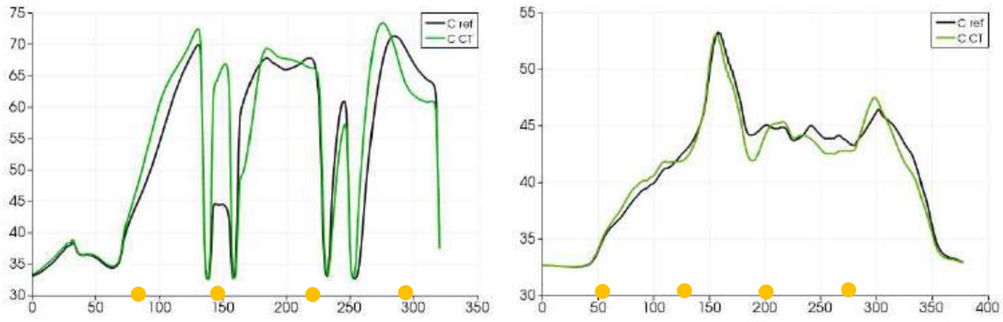


Figure 64: 5th floor NO_2 concentration along southern (left) and northern (right) facades at z=19m (wind south-east)

For south-west wind direction, the presence of the City Trees leads to a changes mainly at the entrance to the Valkenburgerstraat due to the City Trees 7 and 8. The local changes there are between -7 and +2.5 µg/m³ (Figure 65) and decrease with height (Figure 66 Figure 67). Further downwind the street, the changes are minor.

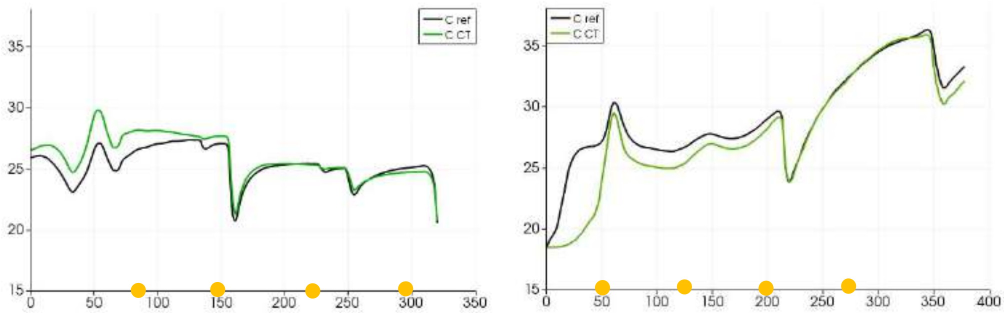


Figure 65: Ground floor NO_2 concentration along southern (left) and northern (right) facades at z=1.8m (wind south-west)

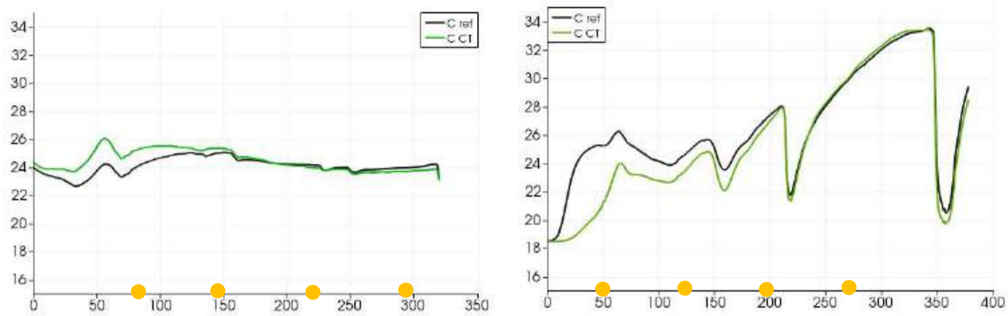


Figure 66: 2nd floor NO_2 concentration along southern (left) and northern (right) facades at z=9m (wind south-west)

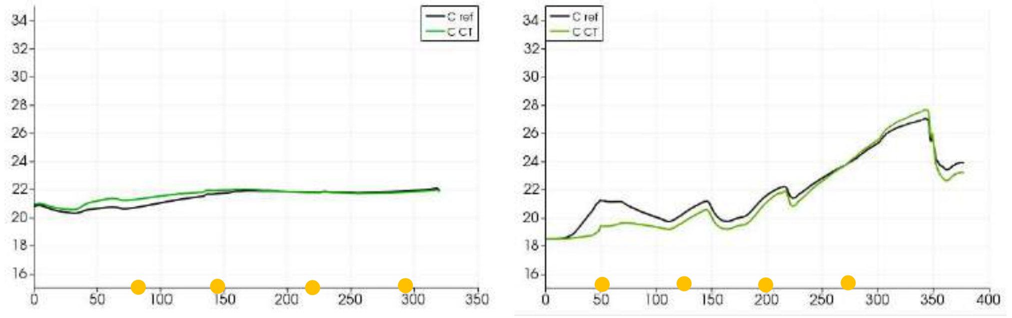


Figure 67: 5th floor NO_2 concentration along southern (left) and northern (right) facades at z=19m (wind south-west)

For wind coming from the south, the concentrations are in between the other wind directions. The maximum increase of NO_2 due to the City Trees is approximately 5 µg/m^3, the maximum reduction approximately 3 µg/m^3 (Figure 68 to Figure 70). Over almost all the facades the NO_2 concentrations are increased due to the presence of the City Trees.

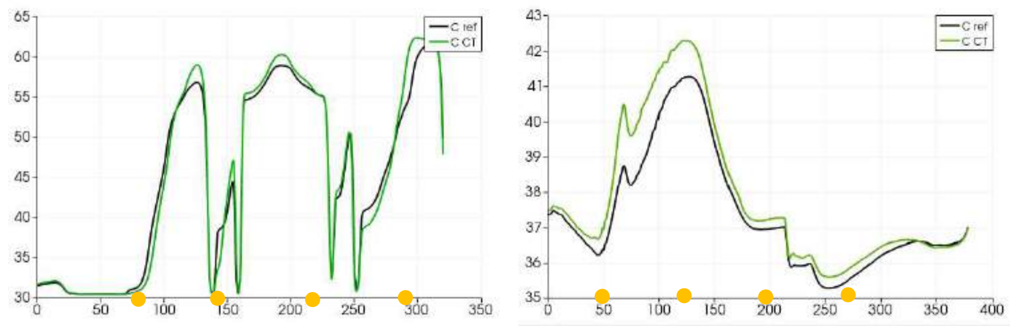


Figure 68: Ground floor NO_2 concentration along southern (left) and northern (right) facades at z=1.8m (wind south)

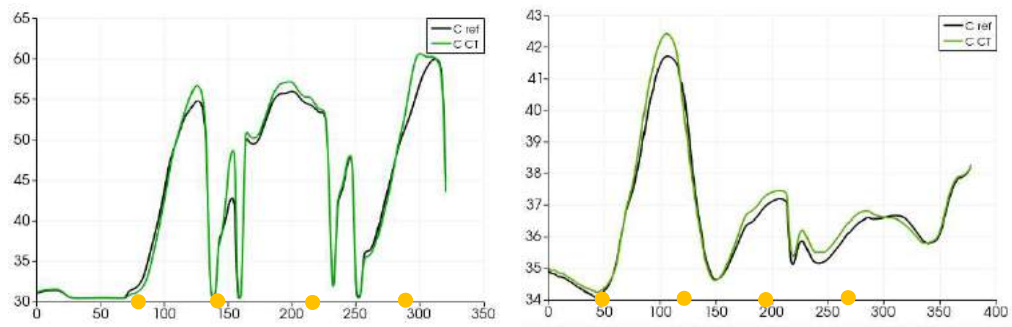


Figure 69: 2nd floor NO_2 concentration along southern (left) and northern (right) facades at z=9m (wind south)

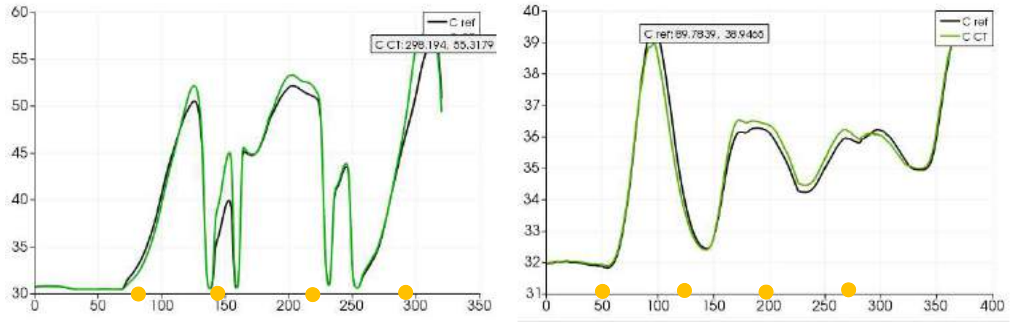


Figure 70: 5th floor NO_2 concentration along southern (left) and northern (right) facades at z=19m (wind south)

3.5.3 *Global comparison of concentrations at building facades*

The area averaged reduction of PM10 concentrations at the building facades is calculated for four different levels: ground level, 1st and 2nd floor, 3rd and 4th floor and 5th-7rg floor. The data is integrated over the whole building front for the different heights. By this, an averaged reduction at each level can be given.

For all wind directions and elevations, the average PM10 values are reduced due to the City Trees.

For south eastern wind, the data is given in Table 4 separately for the northern and southern façade. The absolute reduction in PM10 concentration is between 2.7% (southern facades, ground floor) and 0.5% (northern façade, 5-7th floor). The relative reduction at the northern facades is slightly higher than at the southern facades which is quite interesting since here the absolute level is much lower.

Table 4: Change in PM10 concentration at indicated floor levels wind south-east (21 µg/m³ background concentration, negative values indicate improvement of air quality)

floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	-0.19	-0.9	-26.4	-0.63	-2.7	-29.3
1-2	-0.13	-0.6	-17.7	-0.45	-1.9	-20.8
3-4	-0.12	-0.5	-16.5	-0.31	-1.3	-15.0
5-7	-0.12	-0.5	-18.4	-0.19	-0.8	-12.5

*percentage of traffic contribution[7]

For south-westerly wind (wind aligned with VS) the absolute reductions are lower, between -0.8% (ground floor at northern facades) and negligible the upper levels of the southern facades. The VS emission reduction (with respect to the concentration above background concentration) is still around 15% at the north facades and up to 5% until to the 2nd floor of the southern facades.

Table 5: Change in PM10 concentration at indicated floor levels wind south-west (15 µg/m³ background concentration, negative values indicate improvement of air quality)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	-0.13	-0.8	-17.7	-0.027	-0.17	-6.0
1-2	-0.10	-0.7	-16.5	-0.022	-0.14	-5.7
3-4	-0.07	-0.4	-14.5	-0.005	-0.03	-1.7
5-7	-0.03	-0.2	-13.3	-0.0006	-0.004	-0.35

*percentage of traffic contribution

For the intermediate wind direction from south, the improvement at the southern facades are in between the results of the other wind directions, the maximum improvement is 1.2%. On the northern facades, the changes are lowest but still around 0.1%.

Table 6: Change in PM10 concentration at indicated floor levels wind south (18 µg/m³ background concentration, negative values indicate improvement of air quality)

Floor	North facades VS	South facades VS

[7] "percentage traffic contribution" refers to the reduction of concentrations with respect to the background concentration level. 100% means that the City Trees fully remove the concentration increase due to the traffic emissions in the street thus the concentration would reach background level again. Since the focus of this study is on the investigation of a significant decrease of the absolute concentration level these values will not be discussed in the report; since they might be misleading..

$$percentage\ removed\ traffic\ contribution = \frac{concentration_{wthCityTrees} - concentration_{noCityTrees}}{concentration_{noCityTrees} - concentration_{background}}$$

$$absolue\ change = \frac{concentration_{wthCityTrees} - concentration_{noCityTrees}}{concentration_{noCityTrees}}$$

[-]	absolute change [µg/m^3]	[%]	[%*]	absolute change [µg/m^3]	[%]	[%*]
0	-0.01	-0.06	-2.7	-0.23	-1.2	-17.6
1-2	-0.02	-0.12	-5.7	-0.20	-1.0	-16.2
3-4	-0.03	-0.15	-7.6	-0.13	-0.7	-12.3
5-7	-0.03	-0.15	-10.1	-0.07	-0.4	-9.8

*percentage of traffic contribution

The results for the NO_2 concentration differ from the PM10 concentrations since the City Trees have positive as well as negative effect depending on the concentration level, wind direction and façade orientation.
For street canyon situations, the NO_2 concentrations are increased up to 4.5% at the ground level facades which are in the downwash of the street canyon vortex (Table 7). At the other façade side (here north) the NO_2 concentrations are slightly reduced (max -1.2%).
For situations with the wind aligned with the street, NO_2 changes are observed in the range of +3/-1.5% (Table 8).
For the intermediate wind direction (south), the City Trees increase the NO2 concentrations on all facades in the range of 0.5 to 1.5% (Table 9).
It should be noted that the all changes are small and small changes in these may lead to large *relative* changes. These small changes may be due to specific local flow that may lead to a small increase of clean background air from side streets.

Table 7: Change in NO_2 concentration at indicated floor levels wind south-east (32 µg/m^3 background concentration, negative values indicate improvement of air quality, red colours indicate increase in concentration)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m^3]	[%]	[%*]	absolute change [µg/m^3]	[%]	[%*]
0	-0.32	-0.7	-2.8	2.8	4.5	9.3
1-2	-0.43	-1.0	-3.6	2.7	4.3	8.7
3-4	-0.39	-0.9	-3.4	2.4	3.9	8.3
5-7	-0.50	-1.2	-4.7	1.9	3.5	8.6

*percentage of traffic contribution

Table 8: Change in NO_2 concentration at indicated floor levels wind south-west (18 µg/m^3 background concentration, negative values indicate improvement of air quality red colours indicate increase in concentration)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m^3]	[%]	[%*]	absolute change [µg/m^3]	[%]	[%*]
0	-0.1	-3.0	-7.7	0.37	1.5	5.1
1-2	-0.58	-2.1	-5.6	0.24	1.0	3.6
3-4	-0.36	-1.4	-4.8	0.14	0.6	2.7
5-7	-0.17	-0.8	-5.8	0.15	0.7	4.5

*percentage of traffic contribution

Table 9: Change in NO_2 concentration at indicated floor levels wind south (30 µg/m^3 background concentration, negative values indicate improvement of air quality; red colours indicate increase in concentration)

*percentage of traffic contribution)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	0.45	1.2	6.1	0.003	0.01	0.02
1-2	0.21	0.6	3.1	0.38	0.8	2.1
3-4	0.07	0.2	1.2	0.67	1.45	4.1
5-7	0.04	0.1	0.7	0.059	1.41	5.0

*percentage of traffic contribution

3.5.4 *Annual average reduction of concentrations*

Based on the three investigated wind directions, by which the main flow topologies in the Valkenburgerstraat can be described an estimation for the annual reduction of concentrations at the facades was made. Assuming symmetric flow conditions and comparable effects of buildings on the flow for the opposite wind directions to the calculated ones, annual averages can be (Table 10) calculated. Here, the distribution of the wind direction over the year is taken into account.
The values in Table 10 show that the CityTrees reduce the annual average of the PM10 concentration at the ground floor facades with approximately 0.8%, the absolute reduction is approximately 0.16µg/m^3. The reduction decreases with height, at the upper levels approximately half the reduction is achieved.

Regarding the annual effect on the NO_2 concentration on at the facades, the CityTrees have a negative effect: Almost uniform over the façade height, the NO2 concentration is increased by 0.55%, the absolute increase is 0.3%µg/m^3.

Table 10: Estimation of annual average reduction of PM10 and NO_2 concentration at indicated floor levels (negative values indicate improvement of air quality)

Floor	PM10		NO2	
[-]	absolute change [µg/m³]	[%]	absolute change [µg/m³]	[%]
0	-0.16	-0.80	0.28	0.48
1-2	-0.13	-0.65	0.33	0.54
3-4	-0.10	-0.47	0.37	0.64
5-7	-0.06	-0.31	0.30	0.63

3.6 Global (PM10, NO_2) and local (PM10) performance of City Trees

Based upon the CFD calculations of the concentrations in the VS global estimates were made of the effect of the CT on the concentration of NO_2 in the Valkenburgerstraat. The results of these calculations are presented in the appendix.

In the future the global calculations could be used to make rough estimates of other solutions to solve global air pollution issues. In addition, a detailed analysis of the local performance of the City Trees can also be found there.

3.7 Options for improvement of the performance of the City Trees

A small number of options for improvement with the city trees

3.7.1 The impact of alternative positions of City Trees on the PM10 distributions

In meetings with GCS, the municipality and TNO, GGD and WUR the effectivity of the CT at other locations was discussed. Based on the earlier findings, alternative positions of the City Trees were chosen to improve the overall filtering efficiency of the system. The alternative positions were chosen such that the City Trees are positioned opposite the centre of large (and high) building façades. In addition, the City Trees were concentrated in the street canyon part of the street. By this, the highest cleaning effect with respect to PM10 might be achieved. Since there are mainly 3 large building facades at the south side of the street two City Trees (3 and 5) were placed opposite the central building. An overview is given in Figure 71. The expectation is that the improvement at the facades would only be a few percent but not an order of magnitude.

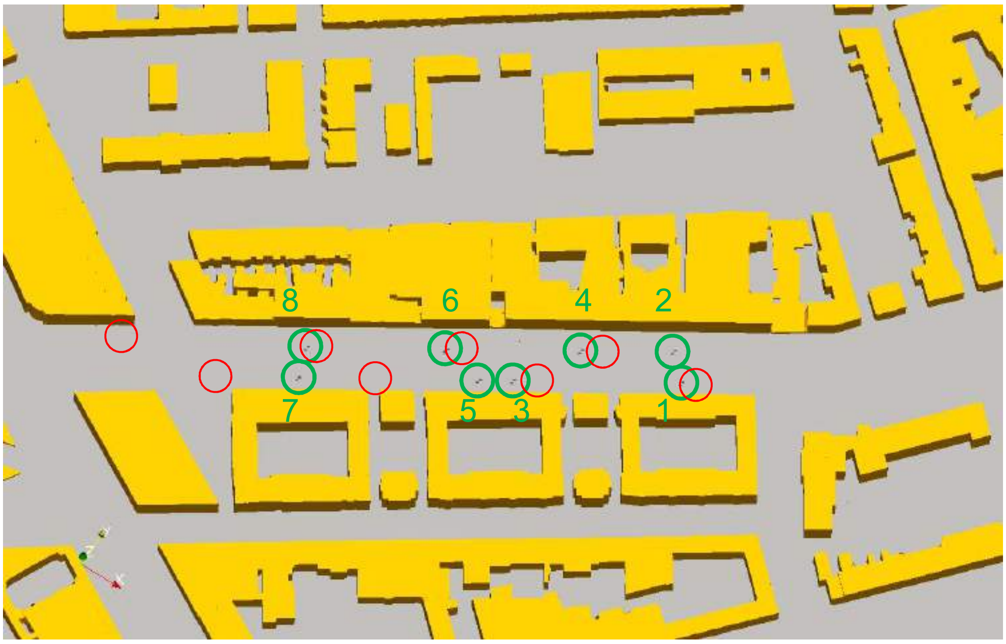


Figure 71: Updated positions (green) and original positions of City Trees (red)

For south-easterly wind, the maximum PM10 concentrations occur in the centre of the street and the hotspots on the southern pedestrian area are improved. Due to the street canyon type of flow and a limited number of City Trees, of course no full emission removal can be achieved (Figure 72, Figure 73). But it is clearly visible that the taken measures show a positive effect.

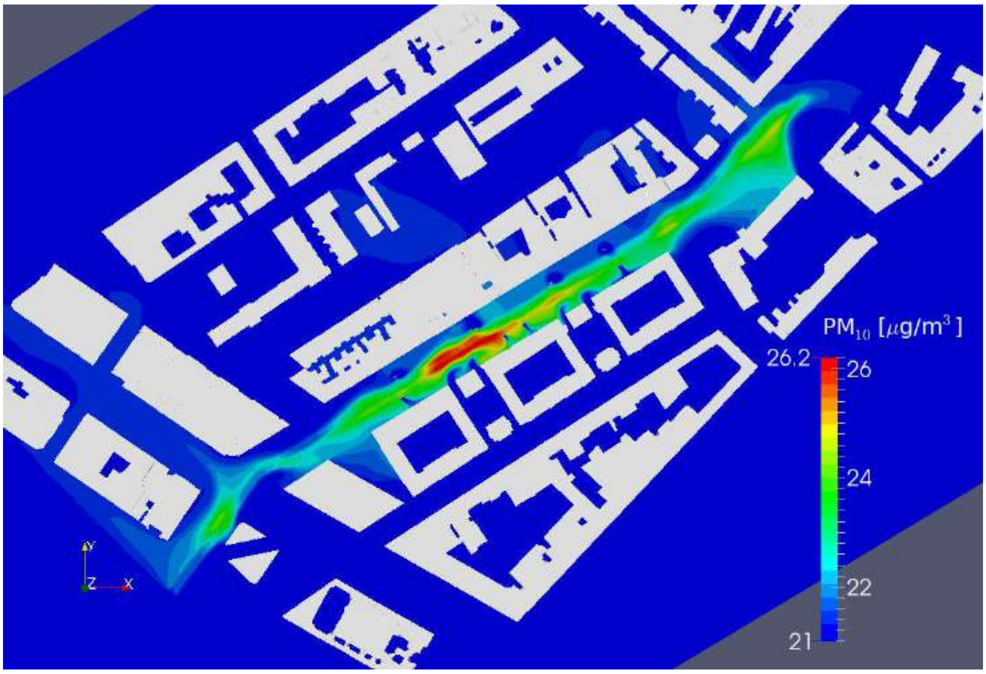


Figure 72: FC1 changed CT position: PM10 concentration due to City Trees. (SE winds, at height 1.5m)

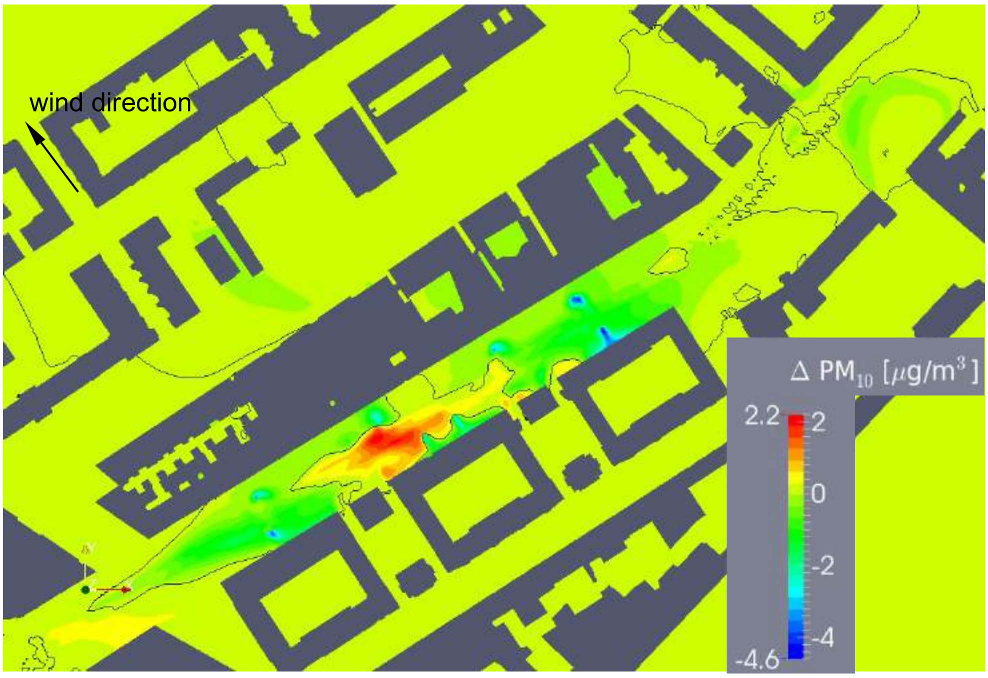


Figure 73: FC1 changed CT position: Difference of PM10 concentration due to City Trees. Negative values indicate an improvement of air quality. (SE winds, at height 1.5m)

Comparable to the original positions, the City Trees have limited impact on the sidewalk area for the south westerly wind direction (Figure 74, Figure 75). The alternative position of the City Trees leads to a slightly enhanced rolling vortex in the street, therefore slightly more unpolluted air is entrained at the northern facades. Due to this, emissions are slightly more dispersed to the south facades.

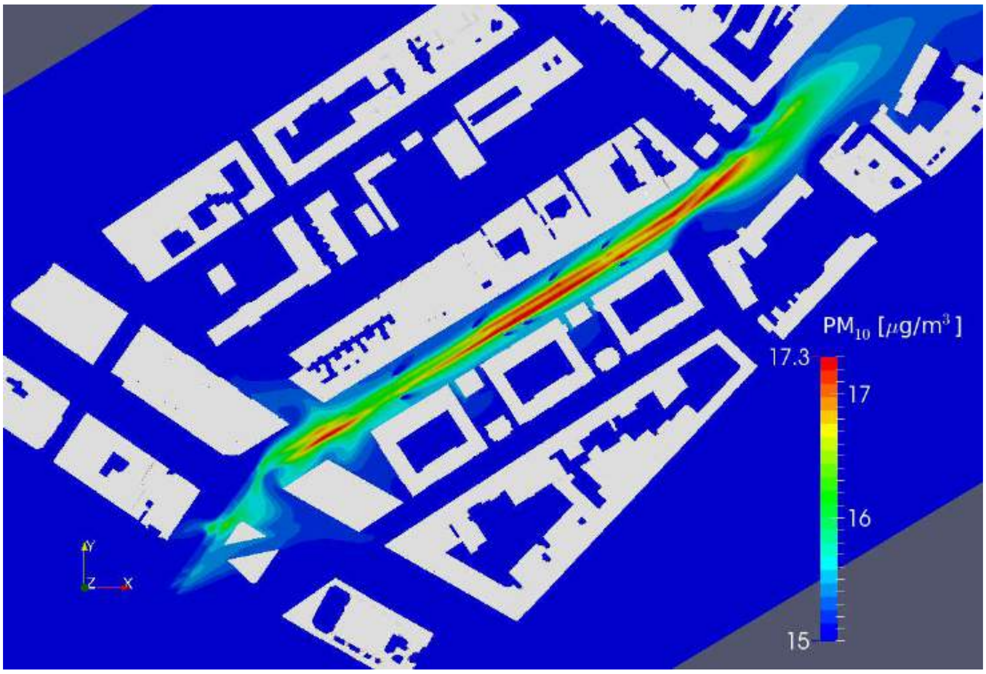


Figure 74: FC2 changed CT position: PM10 concentration due to City Trees. (SW winds, at height 1.5m)

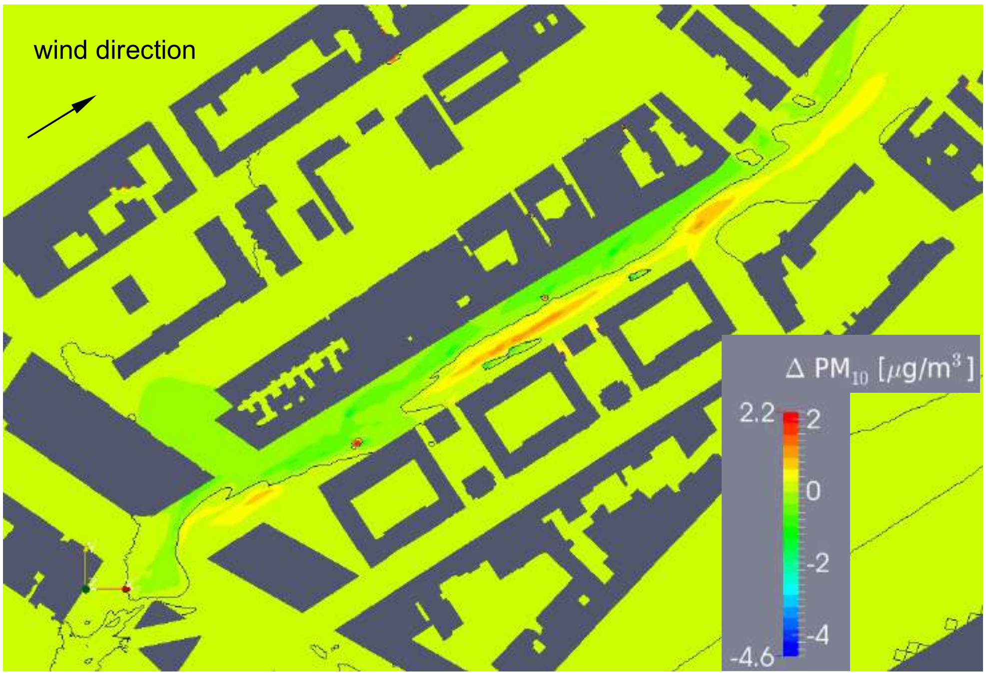


Figure 75: FC2 changed CT position: Difference of PM10 concentration due to City Trees. Negative values indicate an improvement of air quality. (SW winds, at height 1.5m)

Also for the alternative City Tree locations, south wind is an intermediate flow condition (Figure 76, Figure 77).

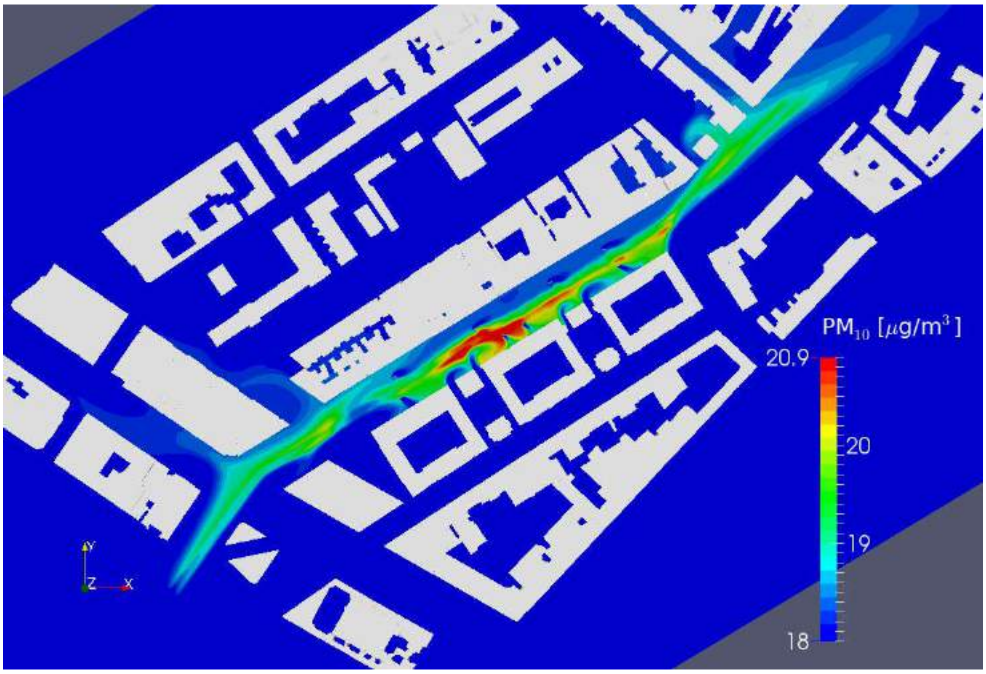


Figure 76: FC3 changed CT position: PM10 concentration due to City Trees. (S winds, at height 1.5m)

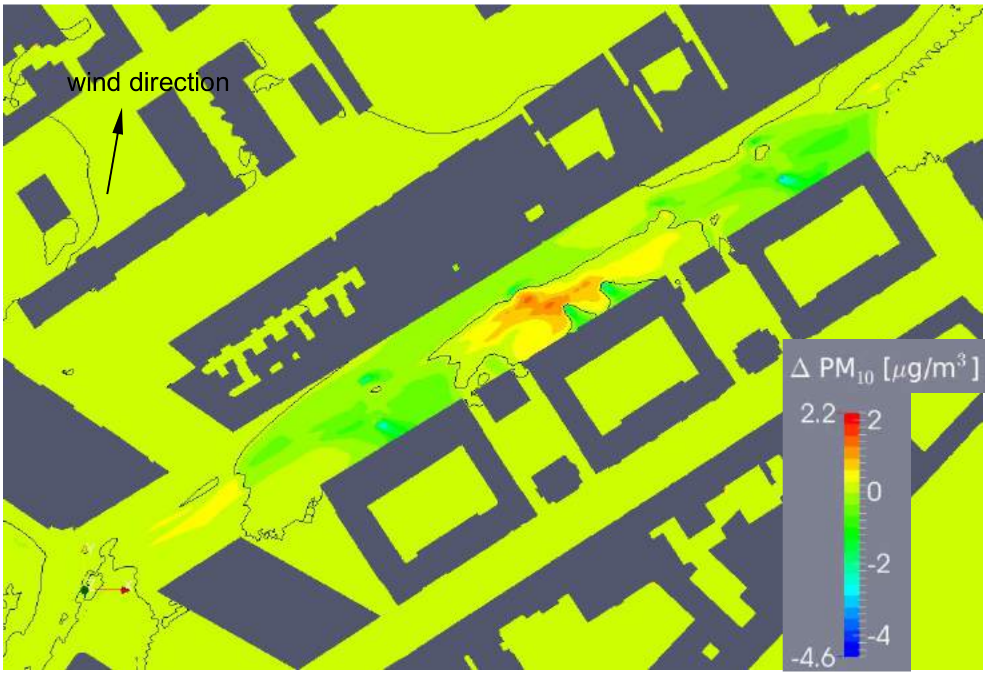


Figure 77: FC3 changed CT position: Difference of PM10 concentration due to City Trees. Negative values indicate an improvement of air quality. (S winds, at height 1.5m)

At the building facades, the City Trees have comparable effect on the PM10 distributions as shown earlier (
Figure 78-Figure 83). Locally PM10 concentrations decrease due to the presence of the CityTree. Due to local flow effects (air entrainment) polluted air still can be trapped locally (compare Figure 79). These local effects have no major effect on the performance on the facades. Globally integrated, concentrations are decreased at all facades levels.
The relative effect at south-westerly wind is high, but die to the low level of PM10 concentration the absolute effect of the City Trees is low.

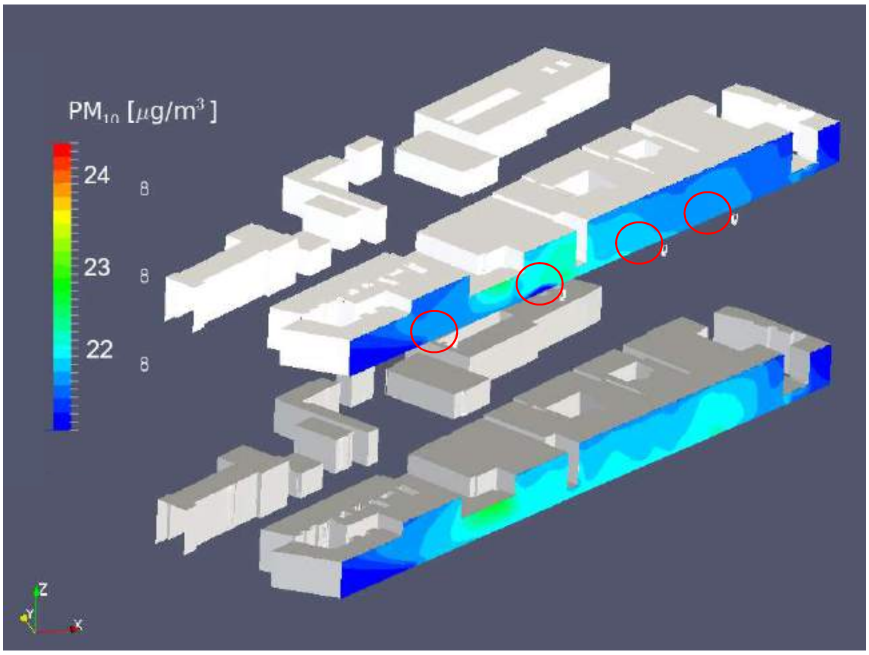


Figure 78: South eastern wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

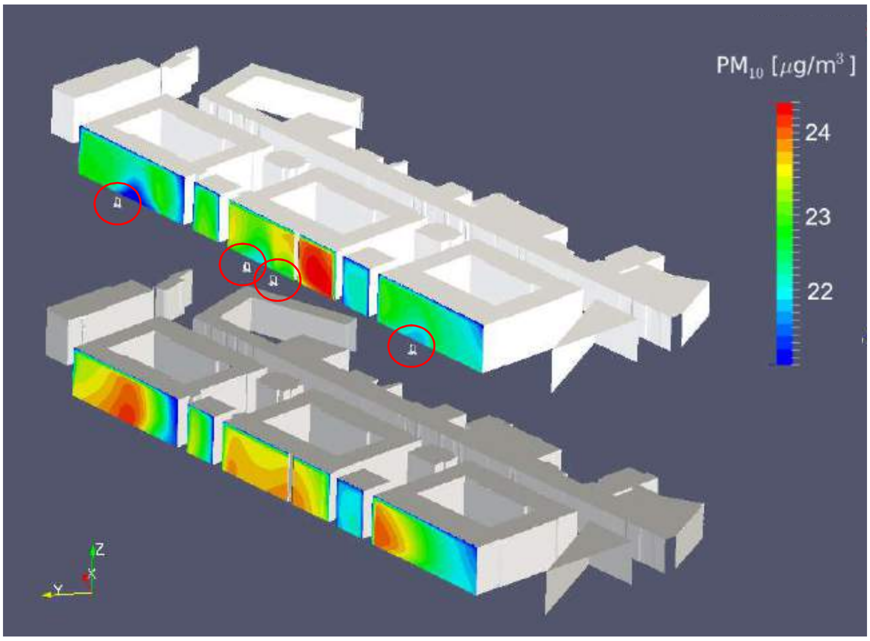


Figure 79: South eastern wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

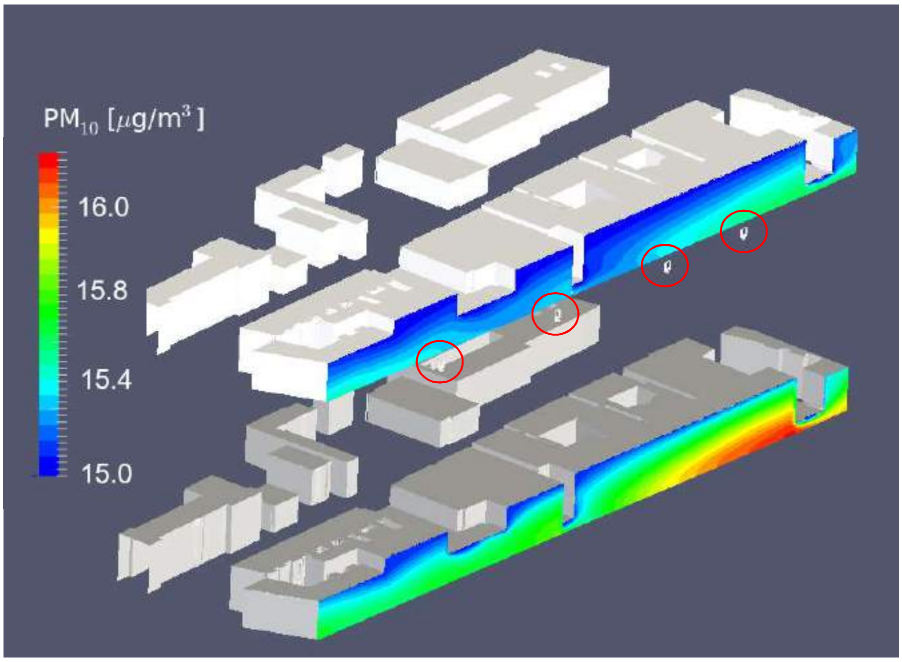


Figure 80: South western wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

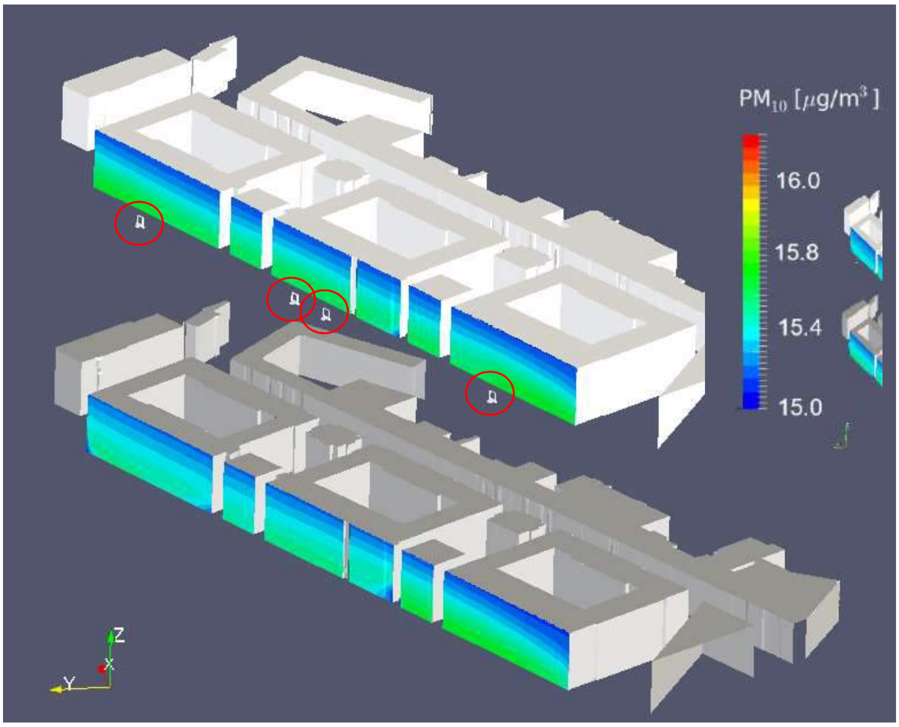


Figure 81: South western wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

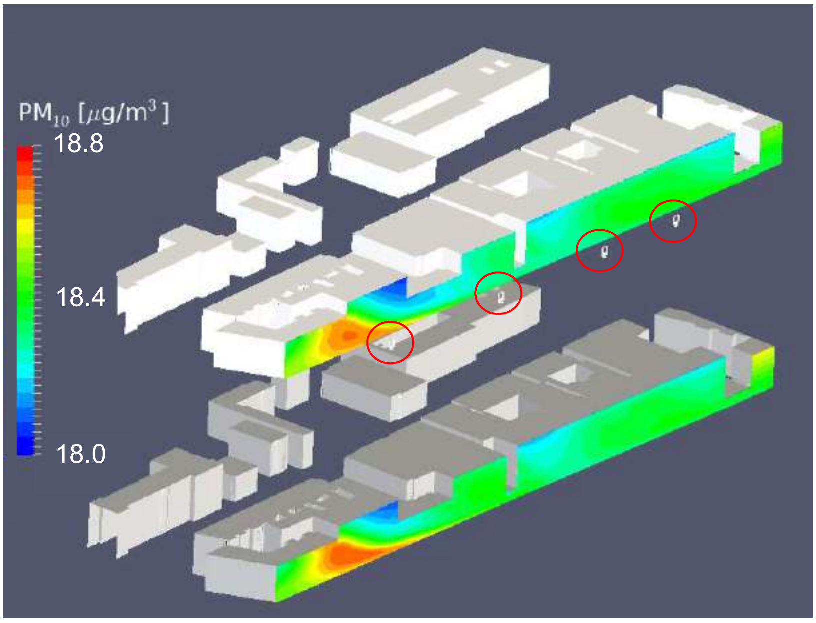


Figure 82: South wind PM 10 concentration along northern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

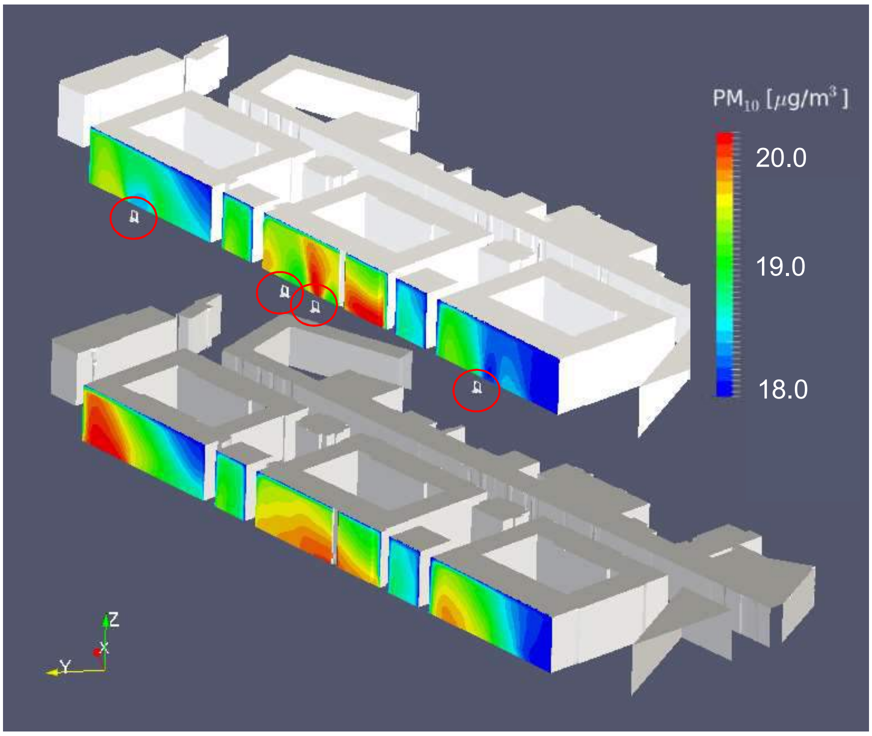


Figure 83: South wind PM 10 concentration along southern facades with (top) and without (bottom) City Trees (position of City Trees indicated)

Analysing the PM10 distributions along the different heights at the facades for the three different wind directions (Figure 84-Figure 92) also shows that local PM10 reductions are highest at ground level and decrease with height. Also as seen before, local increases of PM10 can be observed.

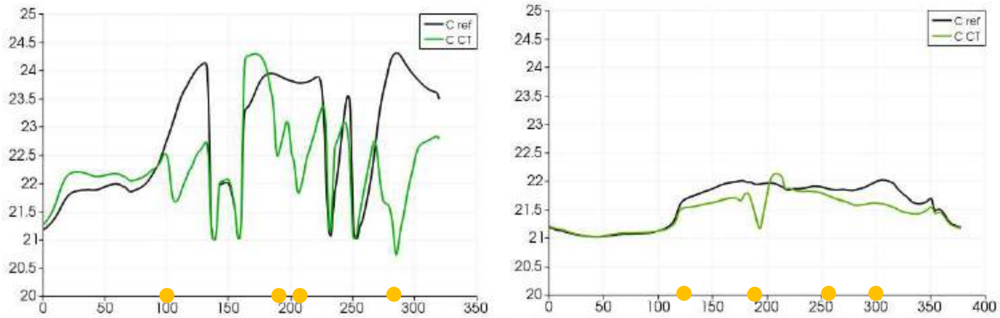


Figure 84: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8 m (wind south-east)

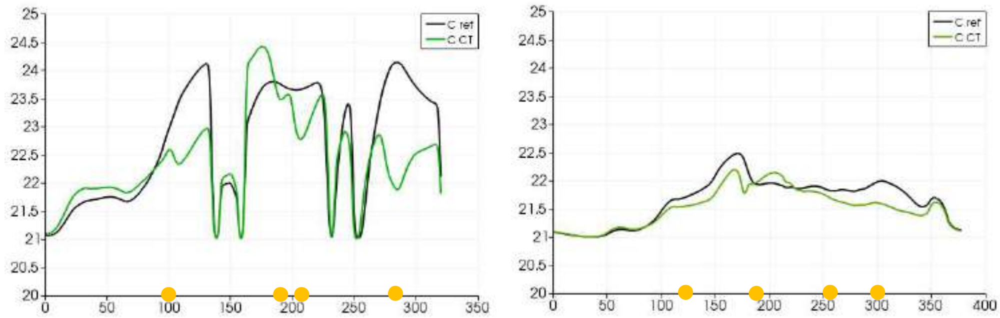


Figure 85: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9 m (wind south-east)

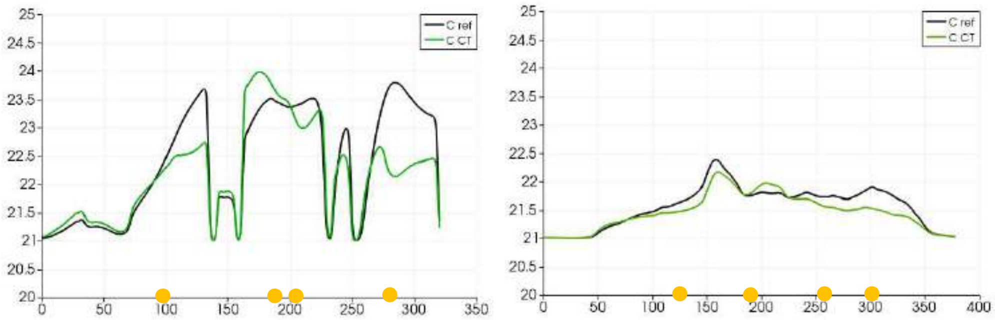


Figure 86: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south-east)

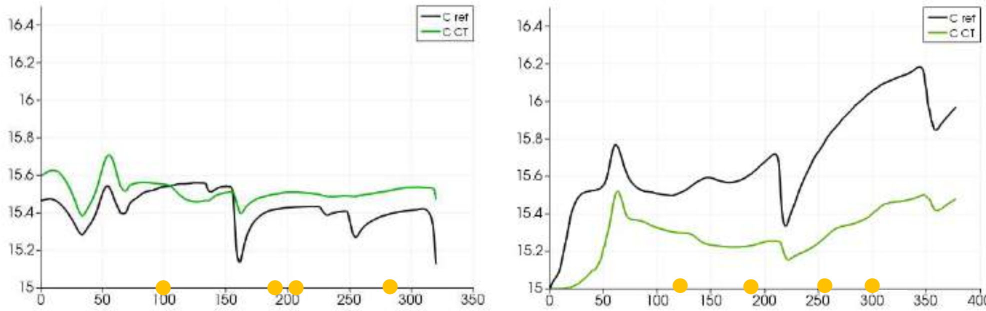


Figure 87: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8m (wind south-west)

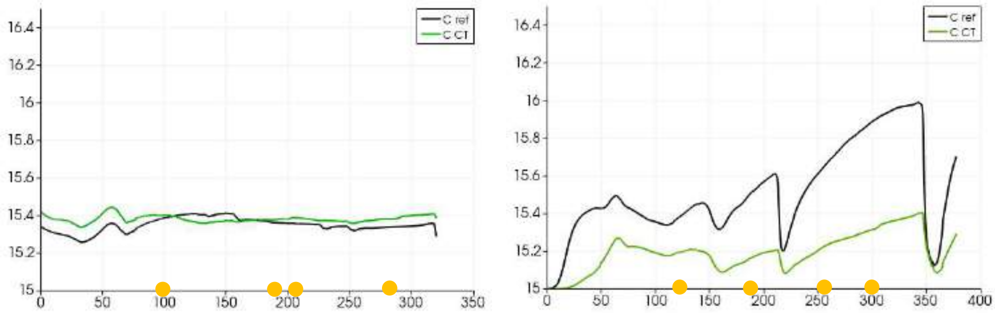


Figure 88: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9m (wind south-west)

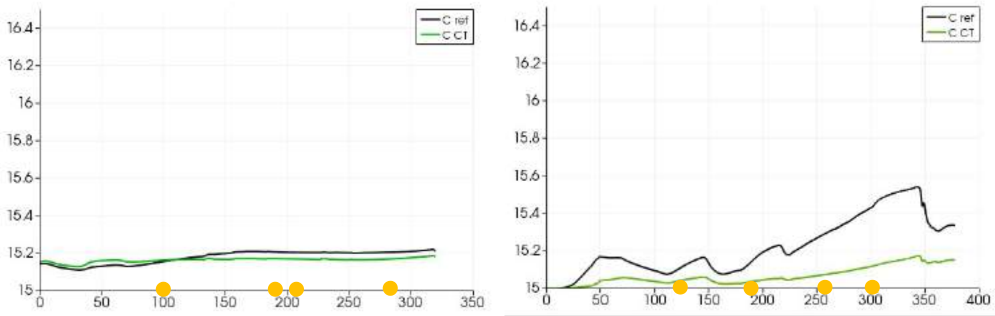


Figure 89: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south-west)

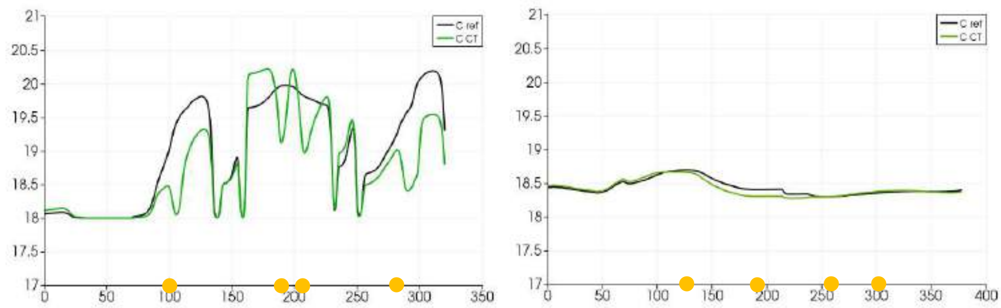


Figure 90: Ground level PM 10 concentration along southern (left) and northern (right) facades at z=1.8m (wind south)

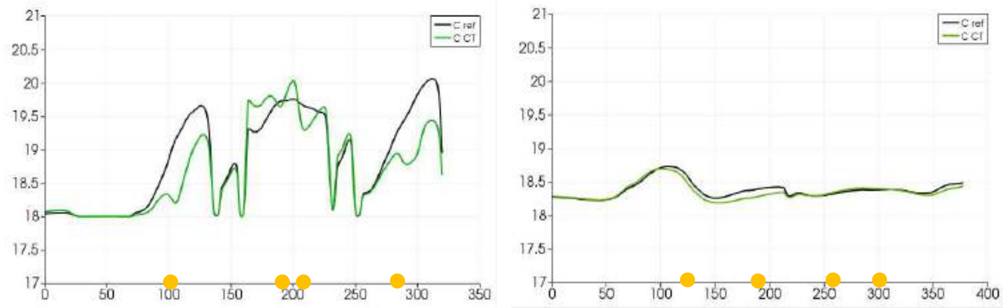


Figure 91: 2nd floor PM 10 concentration along southern (left) and northern (right) facades at z=9m (wind south)

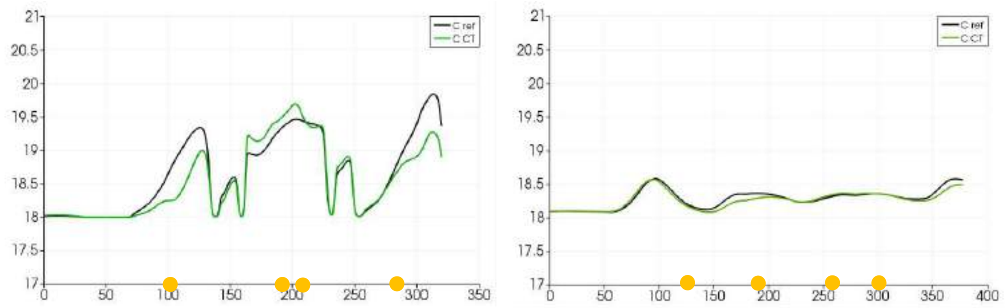


Figure 92: 5th floor PM 10 concentration along southern (left) and northern (right) facades at z=19m (wind south)

For the more relevant cases for south-easterly and southly wind (Table 11, Table 13) it can be stated that the alternative positions help decreasing the concentrations at the heavier polluted street side (south) by approximately 0.5% at ground level. The absolute reduction due to the City Trees is still relatively low (-0.76 µg/m^3 or -3.3% for south-easterly wind.

For south-westerly winds, due to the slight displacement of the large vortex in the street, the concentrations at the southern facades increase (Table 12). The reduction at the northers facades therefore is relatively high. Therefore, the air flow might be sensitive to the flow induced by the City Tree for this condition and setup. Since the global concentration level is low the impact on an annual base are neglectable.

Table 11: Alternative CT positions, change in PM10 concentration at indicated floor levels wind south-east (21 µg/m³ background concentration, negative values indicate improvement of air quality)

floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	-0.16	-0.7	-22.6	-0.76	-3.3	-35.6
1-2	-0.13	-0.6	-18.0	-0.55	-2.4	-25.8
3-4	-0.14	-0.5	-16.0	-0.37	-1.6	-18.8
5-7	-0.13	-0.6	-19.7	-0.23	-1.0	-15.1

*percentage of traffic contribution

Table 12: Alternative CT positions, change in PM10 concentration at indicated floor levels wind south-west (15 µg/m³ background concentration, negative values indicate improvement of air quality)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	-0.42	-2.7	-57.0	0.07	0.46	16.9
1-2	-0.38	-2.4	-60.1	0.05	0.30	11.9
3-4	-0.30	-1.9	-65.1	0.05	0.04	1.9
5-7	-0.19	-1.3	-75.3	-0.02	-0.11	-9.8

*percentage of traffic contribution

Table 13: Alternative CT positions, change in PM10 concentration at indicated floor levels wind south (18 µg/m³ background concentration, negative values indicate improvement of air quality)

Floor	North facades VS			South facades VS		
[-]	absolute change [µg/m³]	[%]	[%*]	absolute change [µg/m³]	[%]	[%*]
0	-0.02	-0.12	-5.2	-0.32	-1.7	-24.2
1-2	-0.03	-0.16	-7.2	-0.25	-1.3	-20.6
3-4	-0.02	-0.09	-4.4	-0.18	-0.9	-16.4
5-7	-0.02	-0.10	-6.6	-0.11	-0.6	-14.3

*percentage of traffic contribution

On a yearly averaged base, the PM10 concentrations are slightly improved on all floor levels further due to the alternative City Tree positions (additional reduction -

0.064 µg/m^3 at ground level). The overall removal capability is still relatively low, but slightly improved from -0.8% to -1.15% (Table 14) of the traffic emissions
For comparison Table 10 is repeated here as Table 15.

Table 14: Alternative City Tree positions, estimation of annual average reduction of PM10 concentration at indicated floor levels (negative values indicate improvement of air quality)

Floor	PM10	
[-]	absolute change [µg/m^3]	[%]
0	-0.22	-1.15
1-2	-0.18	-0.96
3-4	-0.13	-0.72
5-7	-0.09	-0.51

Table 15 original City Tree positions, estimation of annual average reduction of PM10 concentration at indicated floor levels (negative values indicate improvement of air quality), data from Table 10

Floor	PM10	
[-]	absolute change [µg/m^3]	[%]
0	-0.16	-0.80
1-2	-0.13	-0.65
3-4	-0.10	-0.47
5-7	-0.06	-0.31

3.7.2 *Improving air quality in the Valkenburgerstraat using of the City Trees.*

It is difficult to assess what would be needed to improve air quality even further using the City Trees. This is addressed in the appendix. The calculations for PM10 show that a relevant fraction of the emissions is reaching the City Trees (41% for south-eastern wind, 29% for south western wind) which means that the City Trees are cleaning this amount of polluted traffic emissions. With a filter efficiency of 100%, this amount would be removed. Due to the actual filter efficiency of 19%, only 8 to 5% of the overall PM10 traffic emissions are removed
This shows very roughly that if the filter capacity of the City Trees would be 100% between 29 and 41% of traffic emissions would have been removed. This would lead to an improvement of a factor of 5 (41%/8%) and 6 (29%/6%) on average. Comparing with Table 15 to this would lead to an improvement of 5.5 x 0.16 µg/m^3 at the ground floor or an improvement on the facades of 0.9 µg/m^3 or 4.4%. Unfortunately, this result, although estimated using many assumptions, is uncertain but it is still far away from the wanted result. Even if a filter capacity of 100% is used.
Increasing the number of City Trees to for example 16 pieces would of course improve the situation. Similar calculations could be carried out. This would increase the filter capacity by a factor of two. In view of the limited improvement resulting

from improvement of the filter efficiency by a factor 5.5 this does not seem to help much.
For NO_2 increasing the number of City Trees will not improve the situation either. Improving the filter capacity significantly to a very high value is needed to prevent the situation that the concentration at the sidewalk increases due to the City Trees. Figure 18 shows that concentration near the traffic is nearly 80 $\mu g/m^3$ and the background level is around 17 $\mu g/m^3$. To reduce the traffic concentrations to background level would require a filtering capacity of 75% The City Trees increase the concentration near the side walk by some 10 $\mu g/m^3$ of NO_2 compared to a situation without City Trees. If the traffic concentrations would be 12% this effect could disappear. It is difficult to make more accurate estimates of the needed filter capacity.
It is relevant to state these numbers are uncertain especially for NO_2 and new CFD calculations would be needed to support the above raw estimates.

4 Summary and conclusions

Improving air quality in the Valkenburgerstraat using City Trees
In this report we present results of a study that consisted of calculations using a detailed model of emissions and dispersion of air pollutants in the Valkenburgerstraat. The goal of the study was to investigate the effectivity of so-called City Trees to remove air pollutants and improve air quality in the Valkenburgerstraat in Amsterdam.

Assessing the impact of the City Trees in a number of conditions: Approach
A numerical model was used since an assessment of the effectivity of the City Trees on air pollutant concentrations by measurements would require data acquisition over several years. This was not possible since the City Trees would only be in the Valkenburgerstraat for a period of 8 months. In the model eight City Trees were placed in the street at positions selected earlier. Conditions for the calculations were chosen with the aim to optimize chances for a large impact of the City Trees on air pollution levels. The conditions for the calculations were selected based upon expert judgements by scientists from TNO, GGD and Wageningen University. Statistics of concentrations of pollutants and wind speed in Amsterdam were used to guarantee realistic results. By doing this optimal, yet realistic, conditions were ensured as a first result. Data on the capacity of the City Trees to filter pollutants (air flow and filtering factors) were obtained from the manufacturer of the City Trees: Green City Solutions. It was the aim of this study to find out whether the City Trees would reduce the levels of PM10 and NO_2 at the façades in the Valkenburgerstraat significantly i.e. by an annual average between 10 and 20%.

Three conditions were selected and simulated with the model:
- Wind perpendicular to the street (i.e. south-easterly winds). In this run a low wind speed was used and the background concentration was high
- Wind in line with the street (i.e. south-westerly winds). In this run a relatively high wind speed was used and the background concentration was low
- Wind 45^o with respect to street (Southerly wind). This wind direction was chosen as intermediate wind direction

Three runs were carried out for each of those conditions:
- No City Trees in the VS
- Eight non-active City Trees in the VS (only for wind direction south-east and south west and for PM10 concentrations)
- Eight active City Trees in the VS

All calculations were carried out for PM10 (filtering effectivity of 19%) and for NO_2 (filtering effectivity of 5%). The used filter efficiencies were provided by the manufacture of the City Trees: Green City Solutions.

Based upon a detailed analysis of the results we draw the following conclusions. For the base run (without City Trees) we conclude:
- Concentrations show a strong gradient in the street with highest concentrations near the traffic lane
- The PM10 concentration calculated with the model using realistic background concentrations and realistic emissions by traffic in this particular

street are similar to those in the van Diemenstraat for both base runs. The latter is another polluted street in Amsterdam. At this stage the best reference case for a polluted street in Amsterdam. The calculations therefore seemed realistic.
- Similar quality results were obtained for nitrogen dioxide (NO_2)

Results of the calculations with the CFD model in different conditions to obtain an annual average

In a first model run inactive City Trees were positioned in the street. These (now inert) obstacles have only a marginal effect on the concentration levels and profiles in the street. In a second model run the City Trees were activated using parameters in the model according to information provided by Green City Solutions. From the result of these calculations we draw the following conclusions.
- The effects of the City Trees on the PM10 concentrations in the Valkenburgerstraat show an erratic pattern. On the outlet side of the City trees a plume with lower concentrations is clearly visible. This plume mixes up with the more polluted areas leading to a low decrease of the concentration of PM10. The result for NO_2 is even more complex. Areas with a small decrease in concentration are visible but also areas slightly increased concentrations are observed.
- In the runs with south-easterly (SE) winds the decrease in PM10 concentration ranged from nearly around 1 $\mu g/m^3$ for large areas in the street to 4.5 $\mu g/m^3$ in small areas behind the City Trees. In small areas the concentration increased locally due to specific flow conditions caused by the City Trees. For NO_2, the concentrations locally changed between a 40 $\mu g/m^3$ increase and a 35 $\mu g/m^3$ decrease. A clear decrease of concentrations over larger areas was not observed. Local effects are dominant.
- In the runs with south-westerly (SW) winds the decrease in PM10 concentration ranged from nearly around 0.1 $\mu g/m^3$ for large areas in the street to 2.5 $\mu g/m^3$ in small areas behind the City Trees. In small areas the concentration increased locally due to specific flow conditions caused by the City Trees. For NO_2, the concentrations locally change between 6$\mu g/m^3$ increase and 8 $\mu g/m^3$ decrease. A clear decrease of concentrations over larger areas was not observed. Again, local effects are dominant
- In the runs with Southerly (S) winds the decrease in PM10 concentration ranged from nearly around 0.2 $\mu g/m^3$ for large areas in the street to 3.5 $\mu g/m^3$ in small areas behind the City Trees. In small areas the concentration increased locally due to specific flow conditions caused by the CT. For NO_2, the concentrations locally change between 20 $\mu g/m^3$ increase and 16$\mu g/m^3$ decrease. A clear decrease of concentrations over larger areas was not observed. Local effects vary and are dominant

The municipality of Amsterdam was especially interested in the effect of the City Trees on the averaged concentrations at the building façades in the street. These may be summarized as follows:
- With SE winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.19 $\mu g/m^3$ and 0.63 $\mu g/m^3$ on the South side. The NO_2 concentrations near the ground floor facades on the North side

of the street decrease by 0.32 $\mu g/m^3$ and increase by 2.8 $\mu g/m^3$ on the South side

- With SW winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.13 $\mu g/m^3$ and 0.03 $\mu g/m^3$ on the South side. The NO_2 concentrations near the ground floor facades on the North side of the street decrease by 0.10 $\mu g/m^3$ and increase by 0.37 $\mu g/m^3$ on the South side.
- With S winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.01 $\mu g/m^3$ and 0.23 $\mu g/m^3$ on the South side. The NO_2 concentrations near the ground floor facades on the North side of the street increase by 0.45 $\mu g/m^3$ and increase by 0.003 $\mu g/m^3$ on the South side.
- For PM10, the concentrations on the facades are mainly decreasing due to the presence of the City Trees. For NO_2, the concentrations are mainly increasing; locally, increases up to 30 $\mu g/m^3$ are observed
- Although not relevant to the central question it is interesting to see how much PM10 is filtered by the City Trees compared to the contribution in the concentration related to emissions of traffic in the street. It appeared this fraction varies strongly but on average this is at on average this is some 15% of the emissions. In some conditions this fractions amounts to more than 50%. For NO_2 this fraction is variable and can reduce on average up to 3.5 % of the traffic emissions. However, increases up to 5 % are observed at other locations.

The annually averaged effect of the City Trees on the concentration near the ground floor facades was estimated taking into account the probability of the wind directions occurring in 2016. Although this is a rather raw estimate the result is indicative. For the ground floor facades this results in an average decrease across the street of 0.16 $\mu g/m^3$ for PM10 and an increase of 0.28 $\mu g/m^3$ for NO_2. For PM10 the effect on the concentration is highest at ground floor and decreases with height. For NO_2, the effect on the concentration is present in all façade levels.

Although concentrations were calculated under three conditions (especially three wind directions) it is assumed that they cover a sufficient range. The south-easterly low wind condition covers the conditions favourable for the City Trees to have impact. The south-westerly winds cover a standard situation with medium winds and larger mixing than the street canyon situation covered by the SE winds. The southerly wind condition covers an intermediate flow direction. It is assumed at this stage that other wind direction would give similar results with most results lying between the current results. Due to specific local effects of the building arrangements and its effect on the global flow topology, some deviations could occur. These are neglected here.

Options for further improvements
Options to use the City Trees to improve air quality in the Valkenburgerstraat were studied and discussed. These include putting the City trees in other positions and improving the filtering characteristics performance of the CT and placing a larger number of city trees in the street.

- *Impact of the city trees in an alternative positioning*

In discussions of the results of calculations with the original positions it was brought up by Green City Solutions that other positions of the City Trees could lead to improved performance. Therefore, alternative positions of the City Trees were investigated for PM10. The selection of the new positions was done based upon the original calculations. Positions were sought away from side streets and in in front of the middle of buildings. The results are:

- With SE winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.16 $\mu g/m^3$ and 0.76 $\mu g/m^3$ on the South side.
- With SW winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.42 $\mu g/m^3$ and increases by 0.07 $\mu g/m^3$ on the South side.
- With S winds the PM10 concentration near the ground floor facades on the North side of the street decrease by 0.02 $\mu g/m^3$ and 0.32 $\mu g/m^3$ on the South side.
- A raw estimate of the annual average change of concentration near the ground floor facades is a decrease of 0.22$\mu g/m^3$ of the concentration of PM10.
- The effect on the NO_2 distributions was not investigated but is expected to be increased by approximately 0.39$\mu g/m^3$. This is also a very raw estimate derived from the previous results.

  - *Using more City Trees and improving the filter characteristics*

  The impact of these improvements on air quality was investigated using very raw estimates. For PM10 an improvement of the filtering capacity to 100% would not lead to a situation that satisfies the original goal of 10-20% improvement. Doubling the number of City Trees does not lead to the needed improvement. For NO_2 the situation is much more complex. Increasing the number of City Trees probably does not help preventing the observed higher concentrations of NO_2 at the sidewalk. Improvement of the filtering capacity for NO_2 would be needed to prevent the situation where the concentration at the sidewalks is increased because of the City Trees. It is very difficult to estimate the exact filtering capacity needed. New CFD calculations would need to be carried out to improve the quality of these very raw estimates.

Conclusions with respect to the central question

Concluding it may be stated that in the current set of City Trees will not have a significant impact (defined as 10-20% decrease) of the concentrations of particulate matter and nitrogen dioxide on the facades of houses in the Valkenburgerstraat. This was concluded from all calculations with a CFD model that was developed to simulate emission of the pollutants and their dispersion in the street combined with detailed descriptions of the working principle of the City Trees. In none of the calculations the positive effect of the City Trees was larger than 1% on average for PM10. For NO_2 the effect of the City Trees on annual averages was not beneficial. The concentrations of NO_2 on the facades increased by up to 0.5% at the ground floor. The calculations were carried out for a representative series of wind directions and wind speeds and state of the art information on emissions and vehicle velocity. By doing so the calculations were considered to be carried out under realistic conditions. The concentrations calculated in the Valkenburgerstraat compared quite well with concentrations measured in other streets in Amsterdam with dense traffic.
The table below summarizes the results.

The calculations were done for the real positions of the City Trees. Changing these positions to others, considered more optimal, did only lead to a small improvement of the concentrations of PM10.

Table Estimation of annual average reduction of PM10 and NO_2 concentration at indicated floor levels (negative values indicate improvement of air quality, figures in red indicate an increase of the concentration; an unfavourable effect)

Floor	PM10		NO_2	
[-]	absolute change [µg/m³]	[%]	absolute change [µg/m³]	[%]
0	-0.16	-0.80	0.28	0.48
1-2	-0.13	-0.65	0.33	0.54
3-4	-0.10	-0.47	0.37	0.64
5-7	-0.06	-0.31	0.30	0.63

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7 Appendix GLOBAL calculations

The overall system performance is calculated for both wind condition by the amount of PM10 and NO2 which is removed by the City Trees. As an example, two wind directions south-east and south-west are considered.
Comparing the mass flow rates of PM10 and NO_2 entering the City Trees with the ones emitted by the traffic the positioning of the City Trees can be assessed.
The calculations for PM10 show that a relevant fraction of the emissions is reaching the City Trees (41% for south-eastern wind, 29% for south western wind) which means that the City Trees are cleaning this amount of polluted traffic emissions. With a filter efficiency of 100%, this amount would be removed. Due to the actual filter efficiency of 19%, only 8 to 5% of the overall PM10 traffic emissions are removed.
For NO2 the mass flow entering the City Trees is less advantageous due to the lower ratio of the background concentration to the local concentration entering the City Tree. In addition, higher absolute concentrations lead to faster mixing between the release (middle of the street) and the City Trees. Between approximately 7% and 10% of the NO2 traffic emissions reach the City Trees. Due to the low filter efficiency, less than 0.5% of the NO2 emissions are removed.

Table 16: Global PM10 efficiency City Tree installation at VS

Wind direction	Emissions of PM released in VS [10^{-6} kg/s]	PM10 mass flow entering filters [10^{-7} kg/s]	[% of emissions]	PM10 emission removal filters (filter efficiency 19%) [% of traffic emissions]
South east	1.60	6.53	40.8	7.8
South west	1.60	4.60	28.9	5.5
South	1.60	5.46	34.1	6.5

Table 17: Global NO2 efficiency City Tree installation at VS

Wind direction	Emissions of NO_2 released in VS [10^{-6} kg/s]	NO_2 mass flow entering filters [10^{-7} kg/s]	[% of emissions]	NO_2 emission removal filters (filter efficiency 5%) [% of traffic emissions]
South east	16.3	15.7	9.6	0.5
South west	16.3	8.22	5.0	0.25
South	16.3	11.2	6.9	0.34

The local performance of the City Trees is analysed by the local mass flow rates of PM10 at the City Tree locations separately. The higher the PM10 concentration at the filter inlet of the City Tree the larger the amount of traffic emissions which are cleaned. In principle, most of the City Trees show comparable concentrations levels on each street side (City Trees placed at south and north sides). Therefore, the concentrations are more dependent on of the global flow topology in the street due to the meteorological conditions. One City Tree (#8) has a PM10 concentration lower than the background concentration for south-eastern wind which means that hardly any traffic emission reaches this City Tree. Also, for south westerly winds the concentration is lowest which means that this City Tree might better be moved to another location.

As can be concluded from these results the City Trees remove mainly background PM10 (88-97%).

Table 18: City Tree performance of traffic released PM10 removal, wind south-east (PM10 background concentration 21 µg/m^3)

City Tree	PM 10 concentration at inflow City Tree [µg/m^3]	Fraction PM10 from traffic emissions at City Tree [%]
1	23.7	11,3
2	21.2	1.0
3	23.7	11.5
4	21.4	1.8
5	24.9	15.6
6	21.4	1.8
7	23.9	12.2
8	20.9	-0,3

Table 19: City Tree performance of traffic released PM 10 removal, wind south-west (PM10 background concentration 15 µg/m3)

City Tree	PM 10 concentration at inflow City Tree [µg/m^3]	Fraction PM10 from traffic emissions at City Tree [%]
1	15.7	4.3
2	16.3	8.0
3	15.7	4.5
4	16.1	6.6
5	16.0	6.5
6	15.9	5.6
7	16.5	9.4
8	15.5	3.1

Discussion on NOx (NO_2) removal.
It is tempting to try to draw conclusions on the potential impact of the City Trees on NO_2 levels in the Valkenburgerstraat. The following arguments are important:

- The City Trees have a lower filter efficiency (by nearly a factor of 4) for NO_2 than for PM10 and do not filter NO. At the same time, cars emit mainly nitric oxide (NO) and little NO_2. So only directly emitted NO_2 (some 15% of NOx emissions) may be filtered. The conversion of nitric oxide into nitrogen dioxide through reaction with ozone is rather complex in this situation.
- The contribution of traffic emissions on NO_2 concentration in the Valkenburgerstraat is larger than the contribution on PM10 concentration. At the same time the influence of the background is larger for PM10. The position of the City Trees, close to the road, is beneficial because they may then be able to remove emissions of NOx immediately and have a stronger impact on the contribution of traffic to NO_2 levels. The low filter efficiency may on the other hand be a problem. If the concentration entering the City Trees is high, the situation may occur that the City Trees blow air with concentrations higher than the background towards the facades. This way the concentration near the facades may increase (see below). This may be expected for nitrogen dioxide with large emissions and low background.

It may be concluded that it is difficult to draw quantitative conclusions with respect to the impact of the City Trees on levels of nitrogen dioxide in the Valkenburgerstraat without CFD calculations. Mass balance discussions may be helpful:

With the South-Westerly winds it may easily be estimated how much PM10 with background concentrations enters the Valkenburgerstraat (height x width x windspeed x background concentration). This may be compared to PM10 mass entering the street via emissions by traffic. These two numbers may be compared to the mass filtered by the City Trees (calculated from the product of the surface area of the City trees and the air flow and the concentration in air).
The concentration in air which the City Trees draw in may have levels ranging from the background and the concentration near the road depending of the position of the City tree (see Figure 23). Although there might be variation, the air that is taken in by the City Trees will probably lie between this background and the maximum level (in the middle of the road)
Table 20 gives an overview of the numbers for both PM10 and NO_2
The high (maximum) and low (background) concentrations are derived from Figure 23 for PM10. For NO_2, no calculations have been made. Therefore the concentrations have been estimated from the measurements of NO_2 in de van Diemenstraat and the ratio of emissions (PM10/NO_2) (max) and Vondelpark (low). Other columns indicate the mass filtered by the City Trees assuming 19 and 5% efficiency for PM10 and NO_2 respectively. These are compared to the input through background as well as the input from traffic.
The City Trees filter about 1 % of emissions of PM10 from the background and 5% from the emissions from traffic. In the case of NO_2 the difference between he high and low estimates are larger range from 0.9 to 2.5 % for background and 0.6 to 1.6% from traffic emissions. The decrease in concentration related to filtering of PM10 by the City Trees is 0.8 % at the facades (see Table 5)
Based upon this first, rough analysis it is difficult to imagine that the City Trees in this configuration would lower NO_2 concentrations by more than 1% for this wind direction. For SE winds this calculation cannot easily be done. At this stage it is assumed that effect may be similar.

Apart from the global effect of the City Trees with respect to NO_2 which is still slightly positive, the local impact of the City Trees might be negative. In

Table 21 the local concentrations for NO_2 at the inflow and outflow of the City Trees are given. Since the maximum NO_2 concentration entering the City Trees is much higher than background concentration (up to 47 $\mu g/m^3$), whereas the filter efficiency is only 5% the concentration at the outflow of the City Tree can be up nearly 45 $\mu g/m^3$. This means that NO_2 concentrations, larger than the background, may be ventilated by the City Trees in the direction of the boardwalk and the building facades. As a result, the effect of the City Trees on NO_2 concentration at the building facades might be up to 3% higher than without the City Trees. Again, for SE winds these calculations cannot be done easily, and it is assumed that the effect may be similar.

Table 20 Mass balances for PM10 and $_2$O2 in the Valkenburgerstraat . (BG=Background)

	mass entering VS at inlet as background	mass emitted by traffic in VS	concentration entering CT (low, background)	concentration entering CT (high, maximum)
	(10^{-3} g/s)	(10^{-3} g/s)	μg/m^3	μg/m^3
PM10	9	1.6	15	17
NO2	10.2	16	17	47

	filtered by City Trees		Filtered mass as fraction of mass entering through background		Filtered mass as fraction of mass emitted by traffic	
	BG	Max	BG	max	BG	Max
	(10^{-3} g/s)	(10^{-3} g/s)	(%)	(%)	(%)	(%)
PM10	0.08	0.09	0.9%	1.0%	4.8%	5.5%
NO2	0.09	0.25	0.9%	2.5%	0.6%	1.6%

Table 21 Comparison between the concentration of PM10 entering and leaving the City Trees.
*calculated from CFD
**estimated from CFD and CT inflow/outflow concentration

	Concentration CT inflow		Concentration CT outflow (at sidewalk)		Change in concentration at facade	Change in concentration at facade
	BG	maximum	BG	maximum		
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	%
PM10	15	17	12.2	13.8	-0.13*	-0.8*
NO_2	17	47	16.2	44.7	+0.8**	+3**