A parametric study on the effects of green roofs, green walls and trees on air quality, temperature and velocity

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Abstract

A rapid increase in urbanisation and rising populations living in urban areas lead to major problems including increased rate of air pollution and global warming. Assessing the impact of buildings on wind flow, air temperature and pollution dispersion on people at the pedestrian level in the urban design is therefore of crucial importance. In this study, the effect of different forms of urban vegetation including green roofs, green walls and trees on velocity, air temperature and air quality is assessed using Computational Fluid Dynamics (CFD) for a selected area of the East Village. This study indicates that adding a building increases air temperature, pollution concentration, and velocity at the pedestrian level. A parametric analysis is conducted to assess the impact of various key parameters on air temperature, pollution, and velocity at the pedestrian level. These variables include wind speed which ranges from 4-8 m/s at a reference height of 10m, and vegetation cooling intensity which varies from 250-500 $\mathrm{W\,m^{-3}}$. Three scenarios are tested in which the streets have no bottom heating, 2 °C bottom heating, and 10 °C bottom heating. Pollution is simulated as a form of passive scalar with an emission rate of 100 ppb s^{-1}, considering NO_2 as the pollutant. In all cases, vegetation is found to reduce air velocity, pollutant concentration and

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temperature. However, the presence of vegetation in various forms alter the pattern of pollution dispersion differently. More specifically, the results indicate that planting trees (e.g. birch trees) close to the edge of buildings can decrease the air temperature by up to 2-3 °C at the pedestrian level. Increasing the cooling intensity of the vegetation from 250 to 500 W m^{-3} results in significantly lower air temperature. Results also show that lower wind speeds result in higher concentration of pollutants at pedestrian level. Furthermore, it was found that combining green walls and trees is the most effective strategy to improve thermal environment and air quality. The results of this paper provide useful clues for the design of green solutions for improving air quality, outdoor pedestrian comfort, and thermal environment.

Keywords: CFD, building engineering, green roofs, green walls, vegetation, pollution, UHI, urban design.

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1. Introduction

Urbanisation and construction of high-rise buildings lead to temperature rise in cities, a phenomenon known as the Urban Heat Island (UHI) effect, as well as an increase in the rate of air pollution (1, 2). According to Oke et al.(3), urban heat islands can raise city temperatures by 2 to 8 °C. According to Mohajeran et al. (4), the temperature rise will be between 5 and 15 °C. It has been found by Grimmond et al. (5) that by 2030, 61% of the world's population would be living in cities. This suggests that UHI will become more intense as a result of deforestation and global warming. Appropriate actions must be taken ahead of time to prevent these issues. Another critical environmental issue affecting urban environments is air pollution. Pollution comes from a variety of sources, including cars, houses and industry. There are two types of air pollutants: primary and secondary air pollutants. Nitrogen oxides (NO_x) is the common primary air pollutants discharged directly into the atmosphere from emission sources (6, 7). NO_2 in excessive concentration can have negative consequences for human health, such as cardiovascular disease, lung problem, respiratory symptoms, and allergies. High levels of NO_x may have negative effects on plants and habitats leading to loss of biodiversity (8). These are unavoidable changes, so steps must be taken to eliminate or at least lessen their consequences for the sake of people's comfort. Various studies have been carried out in order to reduce the temperature of the air in urban areas. Planting vegetations, changing building design parameters (e.g. aspect ratio, roof shape, etc.), wind speed, wind direction, and the amount of heat source are some of the main methods and parameters that have an impact on UHI and air pollution. Computational Fluid Dynamics has been widely used in the literature to examine the impact of these parameters on the thermal environment and pollution dispersion. For instance, Lin et al. (9) and Chen et al. (10) implemented the green wall on the surface of the building and evaluated the effect of vegetation on the thermal environment. Memon et al. (11) assessed the effect of building aspect ratio and wind speed on air temperature. Some studies have looked at the impact of green roofs on the surrounding environment for outdoor thermal comfort (12). Huang et al. (13) found the average drop in ambient air temperature utilising produced by green roofs in Tokyo is 0.3 °C whereas Chen et al. (14) gave an estimate of 0.1 °C. Baskaran et al. (15) conducted an experimental investigation to determine the effect of a garden roof on air temperature reduction. According to their findings, garden roofs are more effective in reducing heat gain in the summer than heat loss in the winter. The effect of a dom-shaped roof on air quality has been investigated by Hosseini et al. (16). The relative performance of green walls and green roofs for lowering air pollution was investigated by Qin et al. (17). Rafael et al. (18) assessed the impacts of green infrastructure on aerodynamic flow and air quality. Gromke et al. (19) evaluated different arrangement of trees on pollution dispersion.

The majority of studies in this field have focused on the impact of different characteristics solely on air temperature or pollution. None of the works cited above considered the impact of various types of vegetation (e.g., green roofs, green walls, and trees) on air temperature, pollution, and velocity at the same time. In this study, the effects of green roofs, green walls and trees on air quality, air temperature and velocity are evaluated for a range of parameter values using CFD. A selected area of the East Village of London Olympic Park is used as a case study. The CFD model is validated using wind tunnel data by Uehara et al. (20) and simulation results of Baik et al. (21).

2. Problem Definition and Methods

2.1. Test Case 1: Street canyon with bottom heating

2.1.1. Introduction

In this section, a CFD model is used to predict the air temperature in idealised street canyons. The results of the present simulation are compared against wind tunnel data from Uehara et al. (20) and the simulation results of Baik et al. (22). It is worth mentioning that this case study has also been validated by other studies (11, 23, 24).

2.1.2. Computational domain and meshh

In this case study, there are seven street canyons. The building's height, H, and width, W, are both 1 m, as illustrated in Figure 1.For the discretization of this 2D model, a structured (trimmed cell) mesh was used. Using a 0.02m cell size, with a stretching ratio of 1.2, approximately 420,000 rectangular elements were generated. The target street canyon with bottom heating is the middle canyon in Figure 1. Bottom heating is defined as the temperature difference between the ground's surface and the ambient air temperature and represents the effect of the sun warming the earth. The estimated normalised potential temperature and horizontal velocity are acquired at the centerline of the target street canyon.

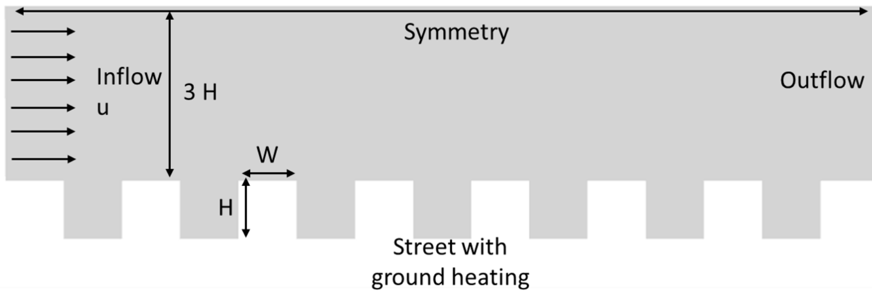


Figure 1: 7 street canyons with bottom heating in the middle street.

2.1.3. Governing equations and boundary conditions

In this case study, the temperature and velocity variations are computed using coupled flow and energy equations. The flow model is based on the RANS equations with the standard k-ε turbulence model, as described in (25–27). The segregated fluid temperature energy model is employed in this simulation. The energy equation is solved using the Segregated Fluid model in STARCCM+, with temperature as the solution variable. The equation of state is then used to calculate enthalpy from temperature (28). The wind speed and temperature at the boundaries are given based on the bulk Richardson number (Rb) which is defined by equation 1.

$$Rb = gH(T_a - T_{g)}/(T_a + 273)u_h^2 \tag{1}$$

where g is the gravitational acceleration, H denotes building height, T_a and T_g stand for the ambient air and the ground temperature respectively. The velocity at the building height is denoted by u_h. The simulated case has a bulk Richardson number of -0.27 and a ground heating of 2 °C. Wind speed at the inlet is set 0.5 m/s. The ambient air temperature at the inlet and outlet set as 20 °C. The outflow boundary has zero static pressure and the top of domain is symmetric. Table 1 represents a summary of the boundary conditions for Test case 4.

Table 1: Boundary conditions for Test case 1

Boundary conditions	**Value/Definition**
Inflow wind speed [m/s]	0.5
Width of street canyons [m]	1
Height of buildings [m]	1
Air temperature [°C]	20
Ground temperature [°C]	22
Richardson number	-0.27
Outflow	Zero static pressure
Top of the domain	Symmetry

2.2. Test cases 2 and 3: Selected areas of East Village of London Olympic park

2.2.1. Introduction

In this section, some areas of East Village are selected and presented in Figure 2a and b. Test case 2 consists of 7 buildings, while Test case 3 is the same as Test case 2 but with one additional building. The focus of this section is on the impact of vegetations (trees, green roofs and green walls) on wind speed, air temperature and pollution dispersion in urban areas. The efficacy of different mitigation measures is quantified and compared in terms of area-weighted average of temperature, pollutant concentration and velocity magnitude.

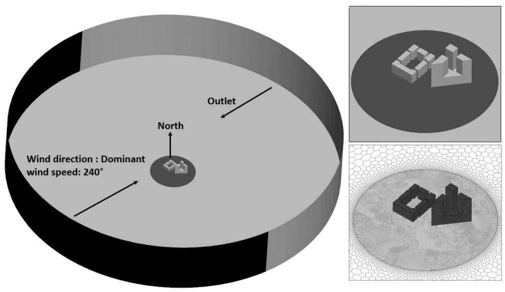
2.2.2. Computational domain and grid

The computational domain for all test cases in this section is the same as in (25). Building heights for Test case 2 range from 30 to 80 m, while those for Test case 3 range from 30 to 102 m. In this part of East Village, the additional building in Test Case 3 is the tallest building. In Test Case 2, there is no vegetation, however in Test Case 3, there are numerous types of vegetation that are defined in Table 2.

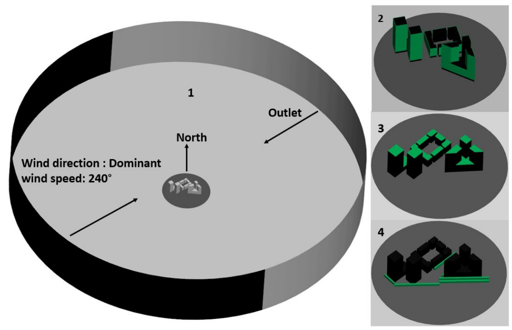
Table 2: Test case 3 with various forms of vegetation.

Case number	**Description**
Test case 3-a	Without vegetation
Test case 3-b	With green roofs
Test case 3-c	With green walls
Test case 3-d	With trees
Test case 3-e	With combination of green roofs and green wall
Test case 3-f	With combination of green roofs and trees
Test case 3-g	With combination of green roofs and more trees
Test case 3-h	With combination of green roofs and more trees: trees 2 m closer to the ground
Test case 3-i	With targeted combination of green walls and trees
Test case 3-j	With targeted combination of green walls and trees

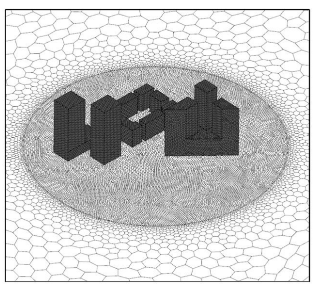
The size, type and location of trees are chosen based on the optimal layout of trees in (25). The thickness of green walls and roofs is 1 m. Green roofs and green walls are represented in this study by a block with a thickness of 1 m, as opposed to the real case where green roofs contain numerous layers (29).The trees are elevated 6 m above the ground, thus the green walls are similarly lifted 6 m. In Test Cases 3a and 3b, green walls and roofs are found on all of the building surfaces which are depicted by numbers 2 and 3 in in Figure 5b. Apart from the influence of individual vegetations, the efficacy of combination strategies was also assessed. Figure 3 from cases e-h shows the combination of greenery. Cases 'i' and 'j' are targeted mitigation choices, and the reason for this configuration will be detailed in section 3.5.
Polyhedral mesh is used for discretisation of the domain with a a thin mesh with two layers on green roofs and green walls (See Figure 2).



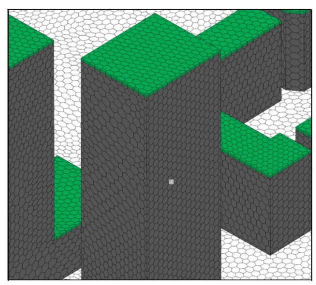
(a) Test case 2



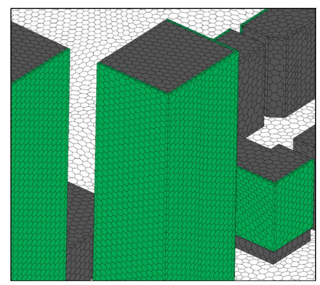
(b) Test case 3



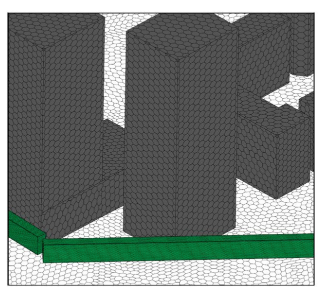
(c) Test case 3-a



(d) Test case 3-b



(e) Test case 3-c



(f) Test case 3-d

Figure 2: Computational domain: (a) Test case 2, (b) Test case 3. Computational mesh for Test case 3: (c) without vegetation, (d) with green roofs, (e) with green walls, (f) with trees.

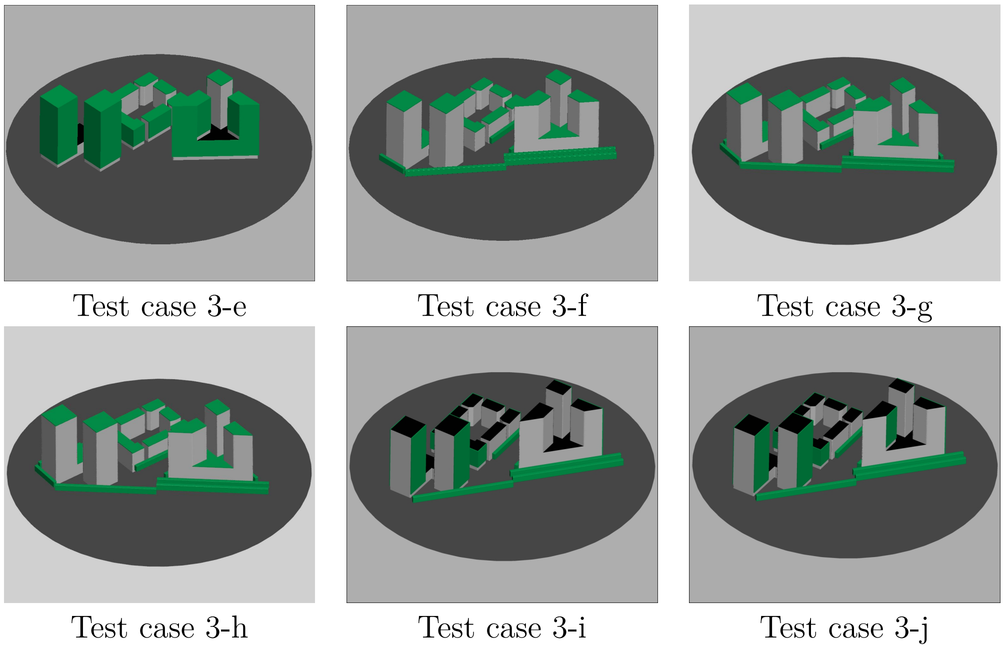


Figure 3: Geometry for Test case 3 with mitigation options.

2.2.3. Governing equations and boundary conditions

The flow and energy equations included in CFD simulations of this test case are the same as those for Test case 1. Heat conduction is neglected, and the walls are considered thin. The simulations are all run in steady state. The flow and surface roughness boundary conditions are the same as in Ref. (25). For all test situations, the air temperature is set to 20 °C. Different ground temperatures were used to generate various heating intensities, which represent bottom heating, the difference between air and ground temperatures.

To evaluate the effect of vegetations (green roofs, green walls and trees) the source terms are added to the equations of momentum, turbulent kinetic energy and energy dissipation. These equations and parameters are described in depth in refs. (25, 30–32).

To account for the impact of vegetation on air temperature, a volumetric cooling power is assigned to vegetation per unit volume which is a function of the leaf area density (LAD). Based on the work of Gromke et al. (30), volumetric cooling power can be estimated as 250 W m^{-3} per LAD unity.

To model traffic emissions at the bottom of the street canyon, additional equations are required. A passive scalar model is used to model pollution. The passive scalar model, which comprises of convection and diffusion terms, is chosen with an arbitrary passive scalar model to build up passive scalar tracking (here pollutant concentration). The diffusion is modelled in this study using a linear eddy-diffusivity model to calculate turbulent viscosity and the turbulent schmidt number which are essential variables for diffusion transport. The reader is referred to (28) to learn more about passive scalar's transport and diffusion equations.

In the simulation of contaminants in urban environments, the turbulent schmidt number plays a key role and its effect on computed concentration was investigated in different studies (31, 33–35). Jiang et al. (36) investigated the effect of Schmidt number on the projected concentration field in this study. He demonstrated that using the standard k-ε model, a schmidt number of 0.4 produces the best results, and that a larger value leads to an overestimation of the concentration field. Since in this study, the standard k-ε is chosen for the simulations and based on the references mentioned here, the value of 0.4 is specified for turbulent schmidt number.

The emission rate is set to 100 ppb s^{-1}, as suggested by Baker et al. (11), and used by Moradpour et al. (37). This number represents the average traffic volume of 930 vehicles per hour (38). The exact location of pollution is the internal circular subdomain in Figure 2 up to the height of 1 m. Different scenarios are investigated in order to assess the impact of various types of vegetation under different conditions. These are as follows in Table 3:

Table 3: Different scenarios for Test case 3

	Bottom heating [°C]	Cooling intensity [$W\,m^{-3}$]	Wind speed at the height of 10 m: [m/s]
Scenario 1	0	250	8
Scenario 2	2	250	8
Scenario 3	10	250	8
Scenario 4	10	500	8
Scenario 5	10	250	4

3. Results and discussion

3.1. Test case 1

The results of this test case consist of the normalised temperature and velocity distributions in the middle of the street canyon. As shown in Figure 4, the accuracy of this model is validated by Uehara's experimental work (20) and the study conducted by Baik et al. (22). The estimated normalised temperature correlates well with the wind tunnel study, as shown in this figure. Furthermore, when compared to the other simulation, it is obvious that the calculated temperature near the ground is very similar to the measured data. Near the ground, the normalised velocity is overestimated while the normalised velocity derived by this model matched the wind tunnel data better than the simulation results, especially at heights beyond the roof level (Z/H>1). Because of changes in simulated settings and experimental setup, the results of this simulation and the wind tunnel data may differ. For example, no roughness was applied to the ground when roughness elements were present in the experimental setup. Moreover, a 3D configuration was employed in the wind tunnel experiment, with buildings displayed as blocks, but the model developed in this study was in 2D. Additionally, the Richardson number in the experiment is -0.21, whereas it is -0.27 in this work. Despite a few minor differences, the overall findings closely matched the wind tunnel data. Based on the results of this validation study, the same strategy for modelling of energy in urban areas with bottom heating will be used in the subsequent sections of this chapter for Test cases 6 and 7.

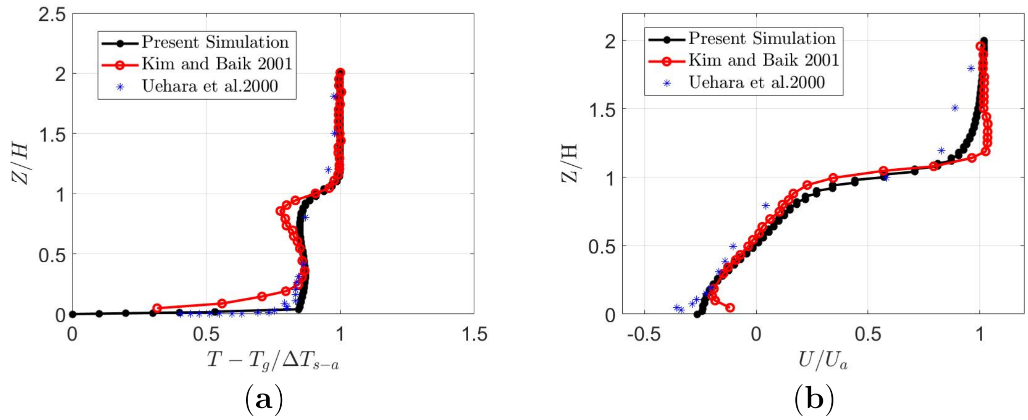


Figure 4: Variation of normalized velocity and temperature with the height in the middle of target street canyon with bottom heating (**a**) normalized temperature, (**b**) normalized velocity.

3.2. Test cases 2 and 3 without vegetation

The simulation conditions for the cases in this section are based on scenario 3 in Table 3, with a bottom heating temperature of 10 °C, cooling intensity of 250 W m^{-3} and an inlet wind speed of 8 m/s.

The results of this section consist of contours of temperature, pollution and velocity at the pedestrian level for Test cases 2 and 3 as shown in Figure 6. In addition, the area weighted average of these variables is taken in three regions of interest, S1, S2, and S3 as shown in Figure 5. S1 is the largest region, and it contains all of the buildings. S2 is the street that is surrounded by all of the buildings and S3 is behind building 2. S1, S2 and S3 have surface areas of 4.4 km^2, 4500 m^2 and 640 m^2 respectively. Based on the results of the following sections, these regions were identified as areas of interest. By comparing the contours of the left and right sides of Figure 6, it is evident that adding a 102 m high-rise building in the direction of the wind can increase the UHI impact, degrade air quality, and create pedestrian discomfort. The results showed that adding building 1 to Test case 2 increased the average temperature in the S1, S2, and S3 regions by 0.32 °C, 0.13 °C, and 0.22 °C, respectively, while increasing the pollutant concentrations by 117, 93, and 132 ppb in the same areas. The S3 region has the lowest velocity magnitude, which is the recirculation zone, and causes the most pollution because pollutants are trapped and do not move in low velocity areas. The average velocity in the large S1 region also increased by 6%. Although this is only a marginal increase, the addition of a building resulted in high-velocity areas in some regions due to the corner and downwash effect. When comparing Test Cases 2 and 3, it appears that the red areas which cause pedestrian discomfort have increased in size dramatically.

The quantitative comparison of these two scenarios necessitates the use of mitigation methods (e.g. vegetations) on Test case 3 to offset the increases in temperature, pollutant concentration, and velocity magnitude. In the next sections, the efficacy of different approaches under various conditions is discussed.

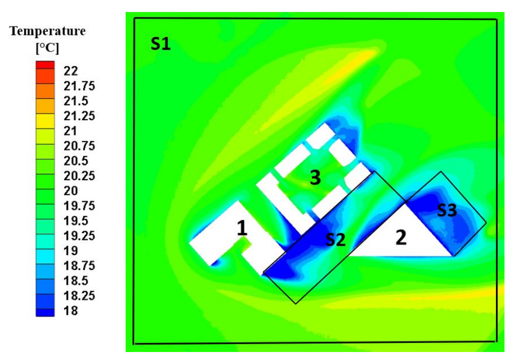


Figure 5: Regions S1, S2 and S3: Area weighted average for temperature, concentration and velocity.

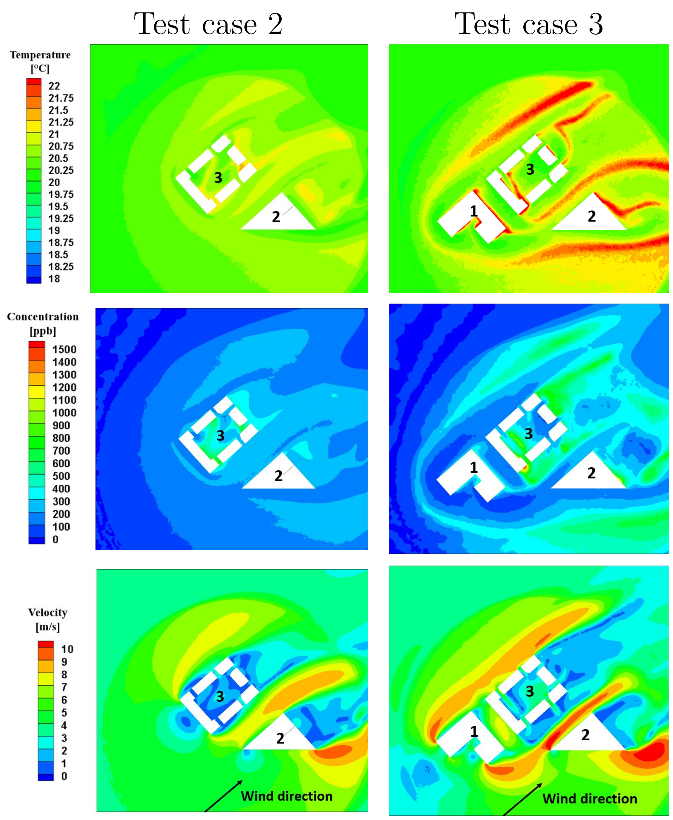


Figure 6: Comparison of temperature, velocity, and pollution contours for Test Cases 2 and 3 at the pedestrian level (2 m), bottom heating: 10 °C, cooling intensity: 250 W m^{-3}, wind speed at the inlet: 8 m/s.

3.3. Test case 3 with mitigation strategies

This section explores how different vegetation layouts such as green roofs, green walls, and trees affect microclimate air temperature, pollution dispersion, and velocity at the pedestrian level. In order to do so, five scenarios are examined. In scenario 1, the mean flow, temperature, and pollutant characteristics are provided in the absence of ground heating. The results of the cases with street bottom heating, referred to as scenarios 2 and 3, are then presented. The difference between scenarios 3 and 4 is that the cooling intensity in the latter is doubled. The difference between the third and fifth cases is that the velocity in the latter is half. In all cases, the average of temperature, pollution, and velocity magnitudes in the region of S1 are decreased by all vegetations. However, the extent of this reduction depends on street bottom heating, vegetation cooling intensity and wind speed which are all discussed below.

- Impact of bottom heating

  When the ground temperature rises, the average velocity magnitude at the pedestrian level goes up, especially in the S1 zone, but a comparison of Scenario 1 to 3 for the case with no vegetation in Figure 9 shows no significant variation in the mean flow pattern between cases with different bottom heating situations. The results of earlier studies (45, 46) show that increasing ground heating improves mean flow inside street canyons. According to these findings, the mean wind speed increased under unstable conditions while decreasing in calm conditions where unstable conditions corresponds to bottom heating cases in this study according to the Richardson number. Under neutral conditions, trees reduce temperature by 0.16 °C. In unstable situations, this is 0.25 °C and 0.51 °C. This means that as the bottom heating rises, vegetations become more effective at reducing temperature. Green roofs and green walls are following the same trend. A slight drop in the average of pollutant concentration at the pedestrian level can be detected as the ground temperature rises (23, 36, 49, 50). As shown in Figure 8, pollution reduction by all vegetations in neutral and unstable situations is nearly identical.

- Impact of wind speed

  Lowering the wind speed increases the temperature gradient on vegetations, as shown in Figure 12. This observation was confirmed by the results of Fu et al. (48). By halving the wind speed in scenario 5 temperature reduction by green walls and trees in S1 region is 0.9 and 0.8 °C, respectively. Because the trees are not planted at the back of buildings 2 and 3, the best comparison may be made in region S2.

Furthermore, in all circumstances, lowering the wind speed at the inlet resulted in higher pollution concentrations. As a result, more windy weather leads to improved air quality (51). According to De et al. (52), the porous nature of the vegetation can produce more mechanical turbulence and absorb more turbulent kinetic energy. Reduced wind speed and recirculation flow (wake region) result in increased shear stress and turbulence which subsequently increased dispersion of pollutants. As a result, in the test cases studied in this section, the largest concentrations are found in the recirculation zones inside buildings 3 and in the rear of building 2.

- Impact of cooling intensity of vegetation

  As expected, the average air temperature drops as the cooling intensity increases, and more cooler air flows into the street canyon as the cooling effect becomes stronger. This can be seen by comparing scenario 3 and 4 in Figure 7, where the only variation is the cooling intensity. Green walls and trees are the most effective solutions for lowering air temperature in the S1 zone, with a drop of 0.5 °C to 0.7 °C when cooling intensity is doubled. In scenario 3, trees reduce the temperature in region S2 by 0.95 °C, while green walls reduce temperature by 1.43 °C in scenario 4. It's worth noting that green walls are on the façades of buildings, and trees are only found in specific regions of high velocities. In comparison to trees, increasing the cooling effects of green walls results in a greater temperature drop.

Despite the fact that the contours are given at the pedestrian level, the temperature difference is shown in two separate planes (Figure 11). This figure depict how convection in the atmosphere distributes heat energy from warmer places near the Earth's surface to higher altitudes in the atmosphere. This graph indicates that the comparison should not be limited at the pedestrian level. When comparing case 'a' with case 'c', as well as case 'd' with case 'b' in this figure, it can be seen that, while trees are able to reduce temper-

ature in more areas at the pedestrian level, green walls are better in general in reducing air temperature if the vertical comparison is also made.
By looking at the contours and the area weighted average of velocity, it is clear that the trees are the best option in reducing velocity among all the tested test cases. However, trees are not as effective as green walls and green roofs in reducing pollution dispersion. In comparison to green walls and trees, the outcomes of this study demonstrate that planting green roofs on tall buildings may not be a cost-effective solution for reducing UHI.

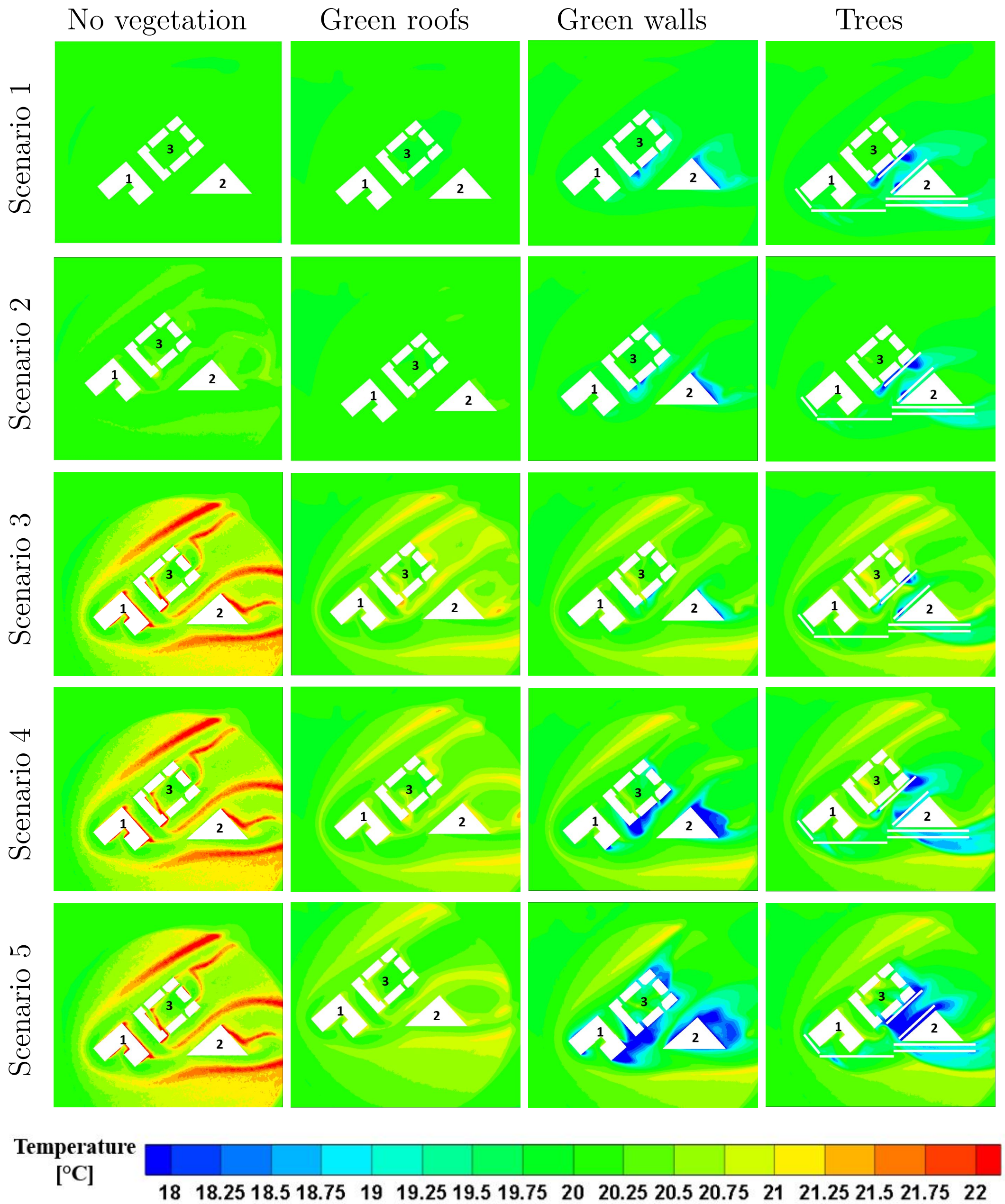


Figure 7: Contours of temperature at pedestrian level

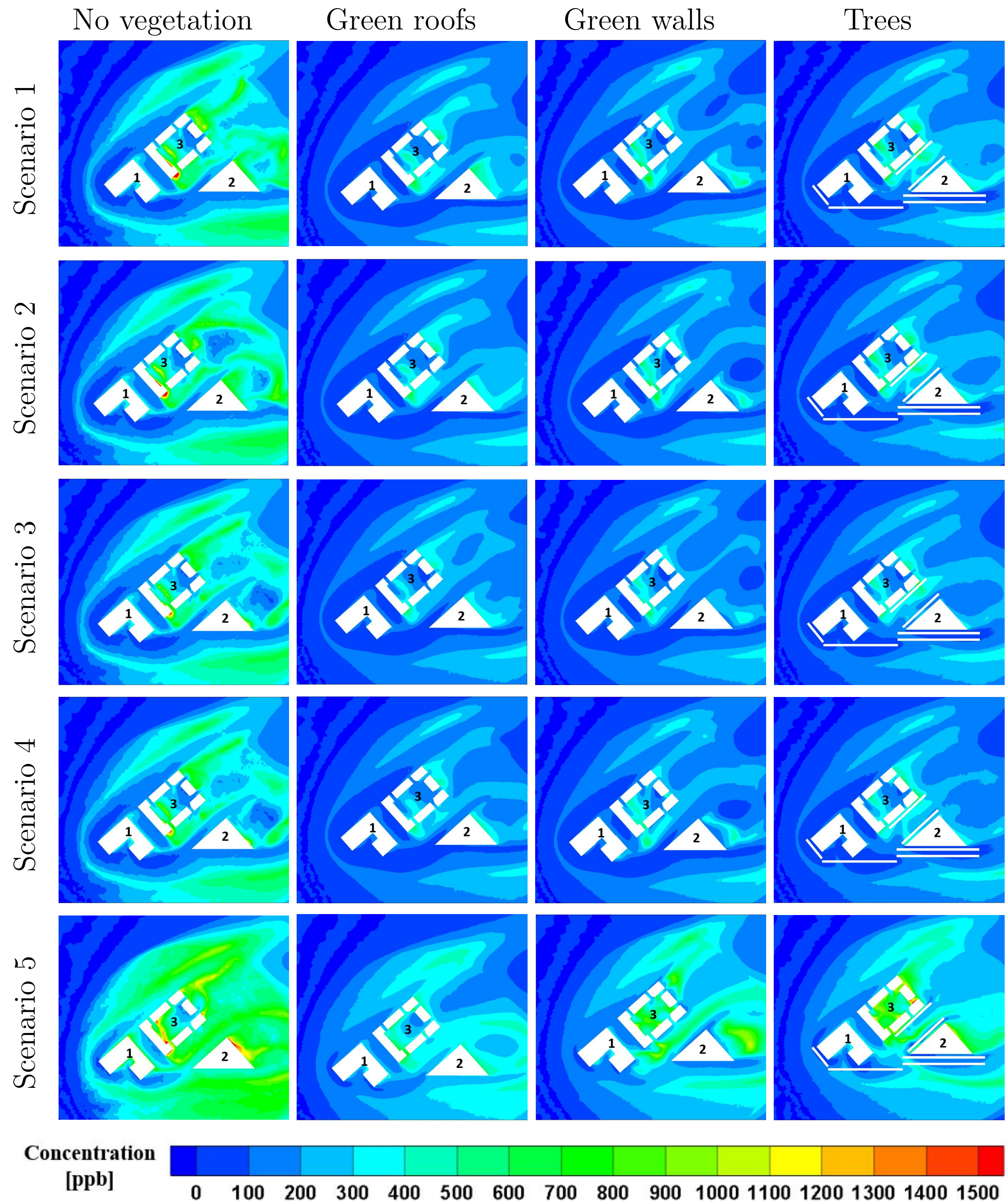


Figure 8: Contours of pollutant concentration at pedestrian level

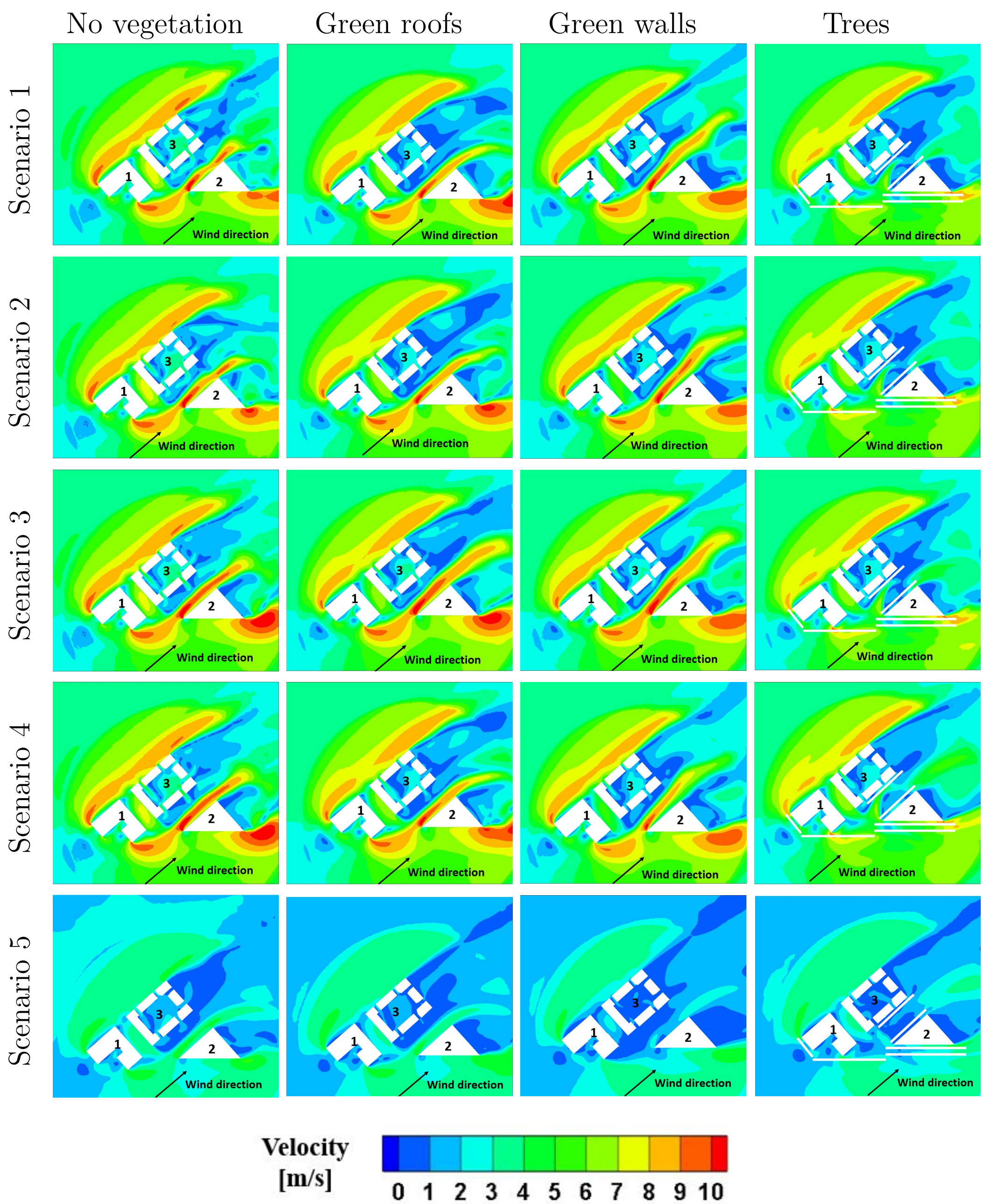


Figure 9: Contours of velocity at pedestrian level

3.4. Test case 3 with combination of mitigation strategies

The simulation conditions for the cases in this section are based on scenario 3. In contrast to the previous section, which looked at the effectiveness of green roofs, green walls, and trees individually, this section looks at how these measures perform when they are combined. The contours of temperature, pollution and velocity are presented in Figure 10. The findings of this section are compared to Test Case 3-a in scenario 3, which is a case with no vegetation.

The average temperature drop in cases 'e', 'f', 'g', 'h' for region S1 is 0.5, 0.51, 0.67, and 0.77 °C. While pollution levels decreased by 49%, 47%, 43%, and 42%, respectively. The average quantity of pollutant is reduced in the S1 region, but not in all sections of the domain, as in the other situations reviewed in the previous section. Trees are added around all buildings in cases 'g' and 'h.' The back of buildings have a lower velocity and as a result, a larger level of pollution are observed than in the absence of vegetation. It can be seen that moving the tree crown 2 m closer to the ground reduced the average velocity by 2% more, while by comparing velocity contours of cases g and h in Figure 10, it can be seen that both cases were able to reduce the uncomfortable pedestrian zone (red areas in the velocity contours) due to the corner and acceleration effect. Furthermore, when comparing examples 'f' and 'g,' where the difference is the number of trees, the average velocity reduction for both cases is almost similar. The worst case scenario is combining green walls and green roofs (case e), which failed to reduce high-velocity zones and only reduced velocity by 5% on average for the S1 region.

In comparison to the individual options (Cases a, b, c and d in section 3.3), case 'g' and 'h' decrease the temperature more than case 'd' by 0.16°C and 0.26°C, respectively, while the pollution level increases slightly. Moreover, whether trees are used alone or in conjunction with green roofs and trees, there is no noticeable difference in the reduction of high-velocity zones. Although combining solutions can combat UHI effect better than individual options, the economic evaluation must also take into account the operational costs, maintenance, and other aspects (54).

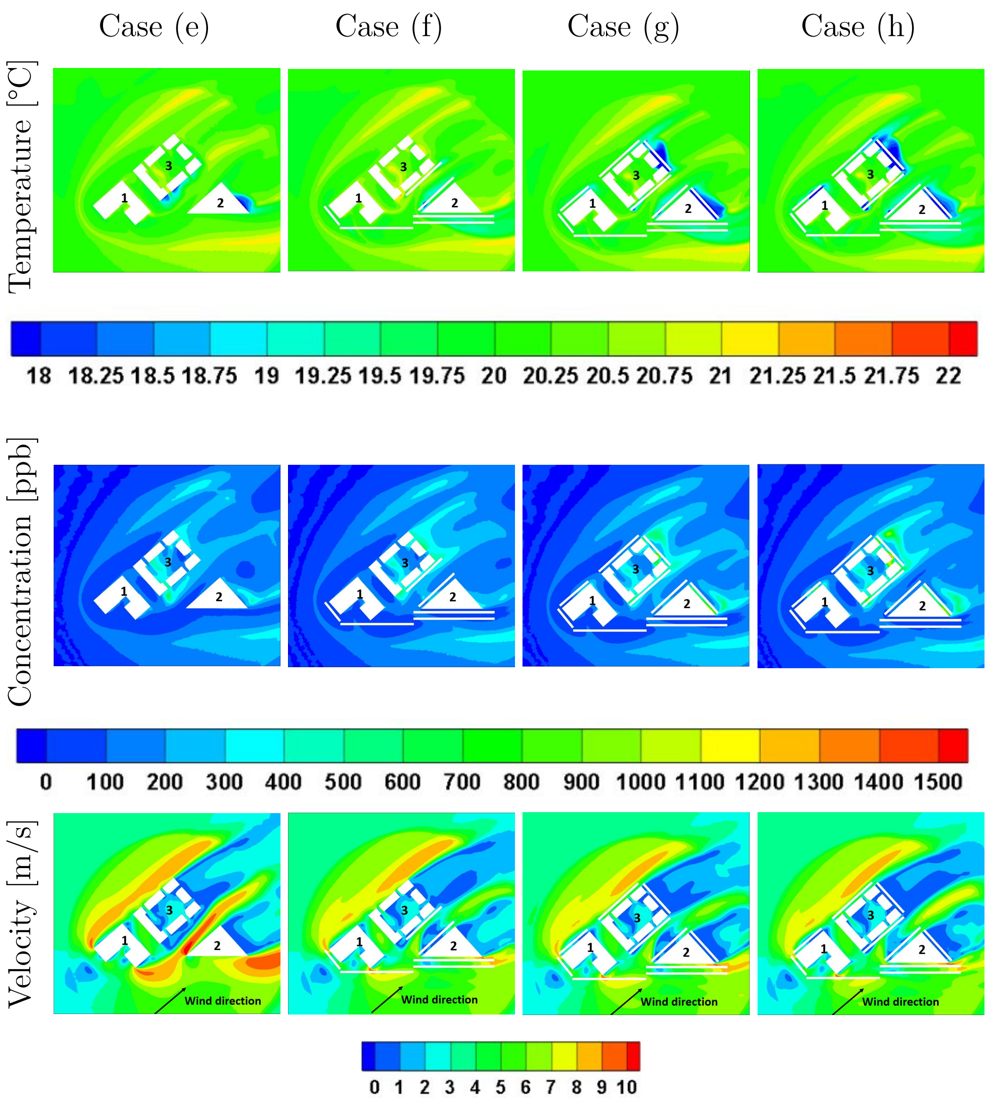


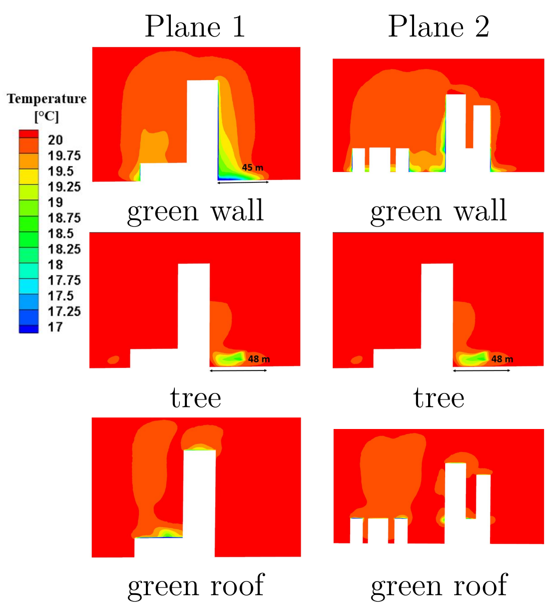
Figure 10: Contours of temperature, pollutant concentration and velocity at the pedestrian level for scenario 3 with combination of: (**e**) green roofs and green walls; (**f**) green roofs and trees; (**g**) green roofs and more trees; (**h**) green roofs and trees with trees 2 m closer to the ground.

3.5. Test case 3 with targeted mitigation

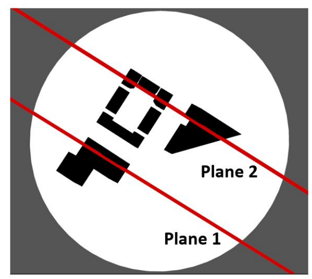
According to the results obtained in previous section, it appears that combining green walls and trees is a viable alternative for reducing UHI, pollution and velocity. As can be observed in Figure 12, the walls facing the wind have a lower temperature gradient than the other walls in these cases. The temperature gradient on walls 1,2 and 3 is clearly the lowest. As a result, the green walls on this surface have been removed. Although the temperature gradient on wall 5 is greater than on the other labelled surfaces, trees are chosen to be planted in front of this wall because the region in front of it is high-velocity zones (see Figure 9). Face 4 is a smaller wall with a colder surface than Faces 1, 2, and 3. So, in this part, the targeted choices are a case where green walls are removed from all 5 numbered surfaces (case 'i') and a scenario where green walls are removed from all numbered faces except face 4 (case 'j'). Since there are no high-velocity areas at the back of the buildings, trees were not planted in these regions.

The results of this section are compared to the Test Case 3 for scenario 3 in Figure 7. The temperature, pollutant concentration and velocity contours for cases 'i' and 'j' are presented in Figure 13. The reduction of the area weighted average of temperature in region S1, S2, and S3 for case 'i' is 0.54 °C, 0.78 °C, and 0.71 °C, respectively, whereas for case 'j,' it is 0.55 °C, 0.7 °C, and 1.03 °C. When compared to Test case 3-d (with only trees), this combination performs better in terms of temperature reduction in the S1 (largest region) and S3 regions. Trees are better in the S2 (street with buildings around it) area. For region S1, the pollution reduction is very similar to the situations with green walls, green roofs, and trees individually, but it performs better in regions S2 and S3. The average of velocity reduction is also comparable to the trees.

In comparison to the application of vegetation alone or other combination strategies, the combination of green walls and trees proved to be a better option. The ideal placement for trees to improve pedestrian comfort, as well as placing green walls on the faces that can produce the highest temperature gradient, are all factors in the optimal combination of green walls and trees. The direction and magnitude of the wind are the most important criteria in determining which walls should be green.



(a)



(b) Plane lines

Figure 11: Contours of temperature at different planes for scenario 4 using green walls, trees and green roofs.

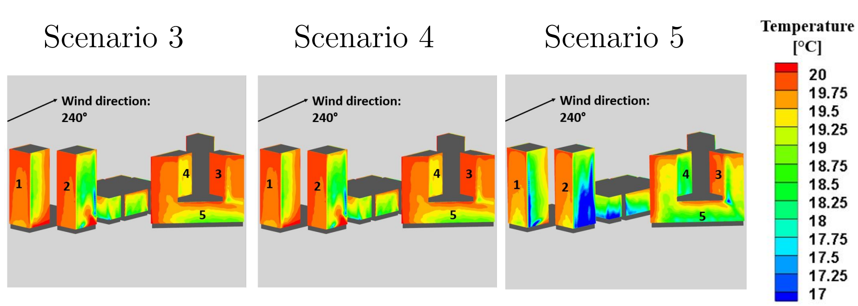


Figure 12: Contours of temperature at the surface of green walls.

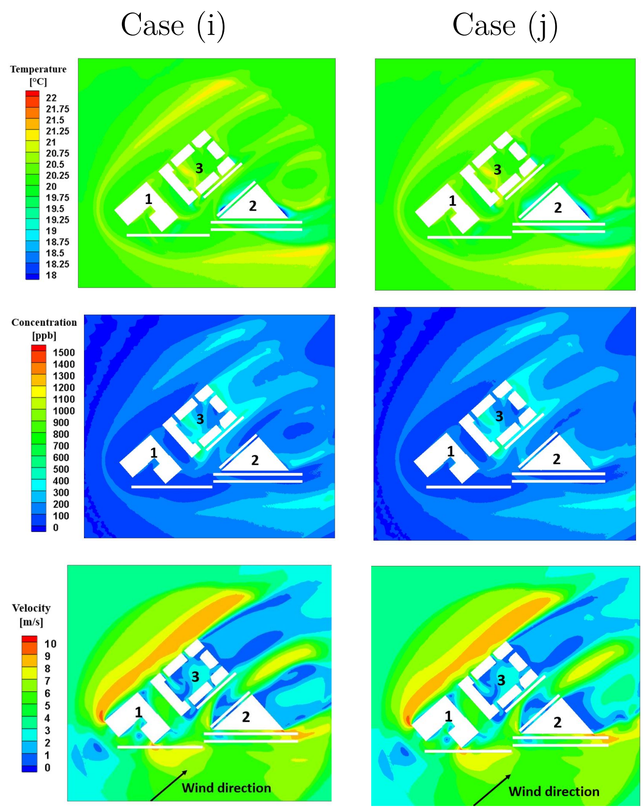


Figure 13: Contours of temperature, pollution and velocity at the pedestrian level (2 m), bottom heating: 10 °C, cooling intensity: 250 $\mathrm{W\,m^{-3}}$, wind speed at the inlet: 8 m/s: (**i**) first targeted combination of green walls and tree, (**j**) second targeted combination of green walls and tree.

4. Conclusion

CFD simulations of flow, energy, and pollution were performed for three test cases and the results demonstrated how including a building into an urban design can aggravate the urban heat island effect (UHI), degrade air quality, and cause pedestrian discomfort. As a result, mitigation strategies (e.g. green roofs, green walls, and trees) to minimize these effects must be offered. Five scenarios were tested which differ in terms of bottom heating, vegetation's cooling intensity and the magnitude of the wind speed at the inlet. The results showed that all vegetations reduced the average temperature, pollution dispersion, and velocity magnitude at the pedestrian level. In addition to evaluating vegetations individually, the effects of combining these measures were also studied. The following main conclusions can be drawn from this study.

- In comparison to green façades, trees are the most effective type of vegetation for lowering velocity due to the corner and downwash effects. Because it has a broader crown and can be planted anywhere on the street, it is the ideal option for pedestrian comfort. Green walls and roofs, on the other hand, are solely on the exteriors of buildings.

- Decreasing wind speed increases the temperature gradient on vegetation, resulting in a greater drop in air temperature at the pedestrian level. However, pollution concentration rises as wind speed decreases. The places with the highest levels of pollution are those areas with recirculation flow.

- Increasing the vegetation's cooling intensity and leaf area density reduces the UHI effect, but has little effect on changing the pattern of pollutant dispersion at the pedestrian level.

- In comparison to green walls and trees, green roofs on tall buildings are less effective at reducing temperature.

- As the ground temperature rises, a slight decrease in the average pollutant concentration at the pedestrian level can be detected. In both neutral and unstable conditions, pollution reduction by all means of vegetation is relatively similar. In addition, with increased bottom heating, vegetation is more effective at lowering temperature.

- Overall, when considering the effects of velocity, temperature, and pollution, a combination of green walls and trees on high-speed wind and tall buildings is the best option.

It is worth noting that the results of this study can be improved in a number of ways. For instance, accurate modelling of radiation provides more realistic results. In order to provide a more reliable predictions of air temperature, radiation parameters such as radiation flux, emission angle, wavelength of radiation, surface absorptivity, reflectivity, and transmissivity, must be taken into account. However, bottom heating is used in this study to represent how the sun warms the earth. In addition, the strength of bottom heating depends on the time of day. While, In this study, it was fixed, and the simulations were run in steady-state mode. In addition, The pollutant emission rate is determined using traffic data, however pollution can also be caused by industry. Furthermore, unlike the non-reactive pollutant suggested in this study, the pollutant in a real case study would be reactive. When the various layers of a green roof or a green wall are modelled, more realistic simulation can be accomplished. Green façades were modelled as a green cube derived from the roof and walls in this research. Planting vegetation on building surfaces, on the other hand, requires numerous layers.

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