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CFD analysis of transpirational cooling by vegetation: Case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands

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A B S T R A C T

The transpirational cooling of vegetation as a measure to mitigate outdoor air temperatures was investigated for a street canyon in the city center of Arnhem, the Netherlands for the meteorological conditions of an afternoon hour on a hot summer day during a heat wave with wind of speed 5.1 m s^{-1} at 10 m above ground and direction along the canyon. Computational Fluid Dynamics (CFD) simulations with locally applied vegetation in the street, i.e. avenue-trees, facade greening, roof greening and all three combined, were performed. The 3D steady-state Reynolds-averaged Navier–Stokes (RANS) equations were closed by the realizable k-ε turbulence model extended with source and sink terms to represent the effects of vegetation on air flow. By specifying a cooling power term in the energy equation, the transpirational cooling by vegetation was accounted for. The strongest cooling by a single vegetative measure was obtained with the avenue-trees with mean and maximum temperature reductions at pedestrian level of 0.43 °C and 1.6 °C, respectively. Facade greening resulted in rather small changes with mean and maximum reductions of 0.04 °C and 0.3 °C, respectively. For roof greening no noticeable reductions inside the canyon were found. In the case of a combination of all vegetative measures, cooling in terms of spatial distribution and intensity overall resembled a linear superposition of those of the vegetative measures solely applied with 0.52 °C mean and 2.0 °C maximum temperature reduction. Overall, the cooling was restricted to the vicinity of the vegetative measures, i.e. up to a distance of a few meters.

1. Introduction

The global mean temperature is estimated to increase by 1.5–4.5 °C till the year 2100 compared to the mean 1980–2000 temperature and the probability of heat waves is expected to rise, e.g. Ref. [1]. For the Netherlands, climate scenarios of the Royal Netherlands Meteorological Institute (KNMI) indicate a mean temperature increase of 1–5 °C for summer and of 1.5–3.5 °C for winter for the same period [1]. Furthermore, in the built environment, in particular in cities, temperatures are generally higher than in the surroundings and in rural areas. This phenomenon, called urban heat island effect (UHI), has its origin in the low short-wave reflectivities (albedo values) of city surfaces, the high heat capacity of building materials, the blockage of outgoing long-wave radiation and natural ventilation by the urban geometry as well as in low evaporation rates due to the lack of vegetation, increased air pollution and anthropogenic heat generation in urban environments, e.g. Refs. [2–4]. For example Oke [2] indicates maximum differences in air temperatures between city and countryside of 4–6 °C at daytime and of 6–10 °C at nighttime. According to Taha [3], average global urban air temperatures can be 2 °C higher compared to those in rural areas. Wilby [5] reports a nightly temperature difference of up to 7 °C between a park in central London and a rural location 32 km away. For the Dutch city of Rotterdam, Heusinkveld et al. [6] report a difference in air temperature between

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the urban and rural area of 7 °C during night and 1.2 °C during day, and Steeneveld et al. [7] show that Dutch cities experience a mean daily maximum UHI of 2.3 °C.

The combination of globally increasing temperatures, the rising probability of heat waves and the urban heat island effect (UHI) causes higher outdoor and indoor temperatures and associated thermal comfort problems, e.g. Ref. [8], an increased building cooling demand and energy consumption, e.g. Ref. [9]. It also implies an amplified risk of heat stress and other health problems among city dwellers, especially the elderly [10]. Heat stress affects people during daily activities and can result in serious health problems and in some cases even in death. During the 2003 heat wave in the Europe, heat stress caused an estimated 1400 to 2200 deaths in the Netherlands [11].

These implications point out the need for measures to reduce high air temperatures in particular during summer heat waves within the urban environment. Possible measures include increasing the short-wave reflectivity (albedo value) of city surfaces, implementing water facilities and implementing vegetation, e.g. Ref. [12]. A way to change the short-wave reflectivity of city surfaces is to paint roof surfaces white. By painting the roof surface of a bungalow house in Sacramento, California white, Akbari et al. [13] changed its short-wave reflectivity from 0.18 to 0.73 and achieved an estimated cooling energy saving of 69% for the period from June to October 1992. Water facilities decrease air temperatures by evaporative cooling. Examples of water facilities are: mist spray, water ponds, fountains and waterfalls. A study by Nishimura et al. [14] in Osaka, Japan showed that a water pond in a park reduced the air temperatures on its leeward side by 1–2 °C. When waterfalls and fountains were additionally operated, air temperature reductions of up to 4–5 °C were measured at a distance of around 10 m at the leeward side of the water pond. Finally, vegetation can be employed to reduce the air temperature. Vegetation provides transpirational cooling and shading, increases the overall short-wave reflectivity of the city, and absorbs and stores less heat than building materials. Examples of vegetation in the urban environment are green roofs and facades or trees in streets or parks. Taha [3] states that soil-vegetation systems can be effective in modifying the near-surface climate by creating oases 2–8 °C cooler than the surrounding area. In research by Wong et al. [15], the thermal benefits of roof top gardens on the environment were studied in the tropical climate of Singapore. It was measured that the maximum ambient air temperature difference at 0.3 m above a green versus a bare roof was at maximum 4.2 °C. However, the cooling effect was limited to the close vicinity of the roof greening. At a height of 1.0 m, air temperature differences were reduced to a few tenths of degree Kelvin. The cooling effect of different vegetation arrangements (park and tree row) in a generic building setup was addressed by Dimoudi and Nikolopoulou [16] with Computational Fluid Dynamics (CFD). For a row of trees along a street they obtained a reduction of the air temperature by 1 °C at pedestrian level (1.5 m above ground) within the leeward first 10 m. Alexandri and Jones [17] modeled the temperature effects of green walls and green roofs for a generic street canyon located in nine different climates with CFD. Their results show that the hotter and drier a climate is, the stronger the effect of vegetation on mitigating high temperatures is. Furthermore, the study showed that green walls have a stronger effect on the inside canyon temperatures than green roofs. The largest mitigations were found for the combination of both green roofs and walls for which peak decreases in air temperature inside the canyon of 11.3 °C for the desert climate of Riyadh and of 3.6 °C for the continental cool summer climate of Moscow were obtained. In a more recent study conducted by Wong et al. [18], a thermal evaluation was made for vertical greenery systems for building facades in the tropical climate of Singapore. They found reductions in air temperatures of up to 3 °C 0.15 m away from the greening system. Again, a noticeable cooling effect was limited to the close vicinity of the greening (<1.0 m). Recently, Fröhlich and Matzarakis [19] studied the impact of ground coverage on thermal stress using the microclimate CFD model ENVI-met [20]. An open space in the city of Freiburg in Germany was redesigned from grass to stone covered but with additional water basins. The redesign resulted at 3 m above ground in increases of the thermal stress expressed in physiological equivalent temperature (PET) by up to 10 °C over the stone covered surfaces and in reductions of 4–8 °C over the water basins.

Despite numerous investigations on the effects of vegetative cooling in urban areas, still relevant and challenging questions are unanswered and knowledge gaps exist. Most of the existing modeling studies consider generic urban environments (e.g. Refs. [16,17,20,21]). Actual urban environments with their complex geometries are seldom addressed except in a few CFD studies (e.g. Refs. [19,22]). However, in those CFD studies spatially rather limited areas are modeled, i.e. only the site of interest and its immediate surroundings, and hence it may be carefully questioned whether or not the local urban flow field and the advection and turbulent diffusion of heat and vegetative cooling as influenced and formed by the buildings and street canyons in the neighborhood are appropriately simulated.

In this study the transpirational cooling effects of various locally in an urban street canyon applied vegetative measures are investigated. The aim is to assess their effectiveness to mitigate high outdoor air temperatures in heat waves and their potential as urban climate change adaptation measures which become increasingly important with global warming. The reduction of air temperatures is of particular interest as it is one of the most crucial variables which impact outdoor thermal comfort, e.g. expressed as physiological equivalent temperature (PET) or Universal Thermal Climate Index (UTCI), see Refs. [23,24], respectively, and furthermore affects the energy consumption of buildings. Three different types of vegetative measures are studied, namely (i) trees planted along a row in a street, (ii) facade greening, and (iii) green roofs. They are separately and simultaneously applied in a case study for a street, the J.P. van Muijlwijkstraat, in the center of the Dutch city of Arnhem. CFD simulations are performed for the meteorological conditions with clear sky and an easterly wind aligned with the along-canyon direction on an early afternoon hour (15 h local time) of the 16th July 2003 during a heat wave in Europe. These conditions are selected since it is the warmest time of the day when mitigation measures are most relevant and the easterly wind direction is typically prevailing during summer heat waves in Western Europe. The reason for choosing a hot summer day during the 2003 Western European heat wave is that those temperatures are considered to occur more often in 50–100 years according to climate change scenarios, e.g. Refs. [1,25]. The main distinguishing feature of this study compared to previous ones is the explicit modeling of the building and urban setup surrounding the street canyon of interest to an, to the best of the authors' knowledge, unprecedented extent. The study area comprises the J.P. van Muijlwijkstraat (length ≈ 350 m) in its center and resolves the surrounding building and urban geometry up to a distance of approximately 300 m in high detail. Furthermore, special attention was given to explicitly resolving the existing vegetation and the additional vegetative measures as well as their aerodynamic modeling in terms of mean flow and turbulence and their modeling in terms of transpirational cooling. Based on our validation studies on the effects of vegetation on mean flow and turbulence as well as on transpirational cooling, the high degree in geometry resolution together with the detailed vegetation modeling, the simulations are considered to enable reliable estimates of the flow and