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Microclimate analysis of a university campus in Norway

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Abstract. Climate responsive urban design that makes use of passive heating and cooling strategies and enhances pedestrian comfort is a key element to a sustainable society. Knowing the impact of different materials, building typologies and arrangements and a building's sensitivity to microclimatic conditions, the energy balance can be enhanced. This study aims to evaluate the microclimatic conditions at the campus of the Norwegian University of Science and Technology, located in Trondheim, Norway. A numerical model was used and validated with punctual measurements on site. The results for air temperature showed a considerable seasonal variation with highest spatial temperature differences in summer and lowest in winter. Regarding the analysis of the wind field, east-west passages were identified as problematic. The influence of the seasonal changing leaf area density of the vegetation had a visible but minor influence on the wind field. The calibrated model will be used for further research on the influence of new building bodies on microclimate and thus building energy demand and pedestrian comfort.

1. Introduction

Ongoing urbanisation, population growth and a steadily warming climate put enormous pressure on cities worldwide. Environmental conditions and anthropogenic pollution of the air, soil and water pose an increasing threat not only to the ecological equilibrium but also to people's health [1]. Through their fabric, consumption of resources, emissions, shape and pattern, urban areas are a massive interference with nature. They are able to significantly change meteorological conditions at the microscale (< 2 km; microclimate) and mesoscale (< 200 km; mesoclimate) [2]. One of the most well-known phenomena of human-induced modification of climate is the urban heat island effect (UHI). It describes the distinct warmth of an urban area compared to its rural surroundings [3]. Many scientific publications have reported the UHI across virtually all climate zones and settlement sizes [4]. Urban-rural temperature differences (UHI magnitude) typically range from 1–3 K. Occasionally, UHI magnitudes of 10–14 K were reported during anticyclonic conditions [5, 6].

The summer heat wave of 2003 in Europe is an alarming example of how devastating climatic conditions can affect our lives. In France alone, 15 000 excess deaths were registered during only three weeks in August [7]. Seven years later, a heat wave struck Moscow with close to 11 000 excess deaths during the 44-day heat wave period [8]. Therefore, and because of increasing city populations, the evaluation of the urban environment has drawn ever-increasing attention in the past decades to make cities more resilient to elevated temperatures. Especially with the advancement of computational power, numerical tools are increasingly used for microclimate analyses [9]. They allow for instance investigating the impact of new building projects within the development of urban districts on local



microclimatic conditions [10], the effectiveness of mitigating measures for the urban heat island UHI [11], or the evaluation of outdoor comfort [12].

However, not only temperate or warm-climate regions are affected by climate change and rising temperatures. In 2018, for the first time since the beginning of the recordings in 1920, the arctic city of Tromsø in northern Norway experienced a “tropical night” where temperatures did not drop below 20 °C. Additionally, only two out of the last 30 years had a lower mean annual temperature than the mean of the norm period from 1961 to 1990 in Norway [13]. Studying urban microclimate thus also gains interest in cold climate countries where summers are usually cooler. While numerical studies on urban microclimate are quite common especially since the beginning of the 2000s, in high latitude locations close to the Arctic Circle they are scarce [9].

The 0.26 km² Gløshaugen university campus in Trondheim (Norwegian University of Science and Technology, NTNU), Norway (63.4° N, 10.4° E) is currently in the early stages of redevelopment. About 90 000 m² of gross floor area are planned to be added to the current building stock until 2027. This study aims to investigate the current microclimatic conditions of a part of the campus (see Figure 1 and 2).

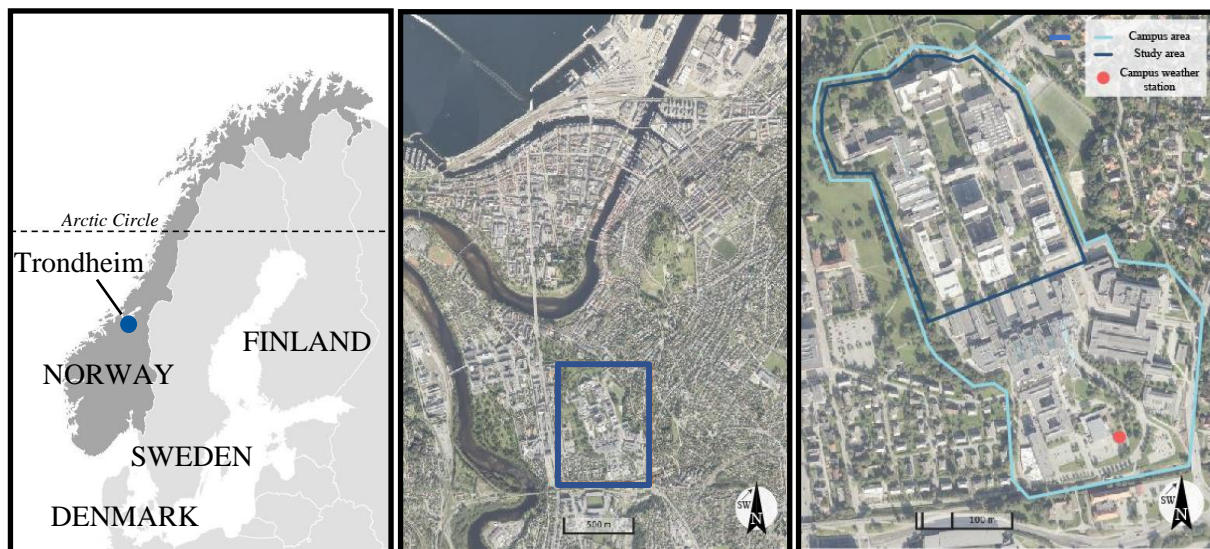


Figure 1. Location of the study area of NTNU campus within Norway and Trondheim (aerial photographs from the Norwegian Mapping Authority www.kartverket.no).

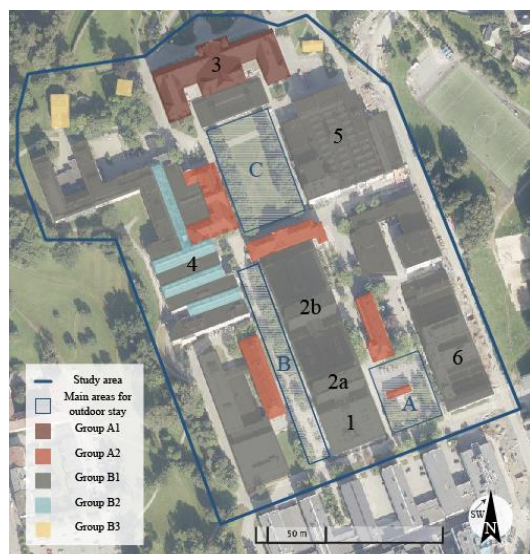


Figure 2. The study area with the building categories and the location of the main areas of outdoor stay: a small grass area (A) between the cafeteria (1) and the Berg-building (6) with seating possibilities; a pedestrian zone (B) west of the central buildings 1 and 2 (2a and 2b) with several seating possibilities close to the cafeteria; a grass area (C) behind the main building (3), east of the Elektro building (4) and west of the VATL (5) with deckchairs during the summer.

2. Methodology

In this paper, two methods are being applied: field measurements and numerical simulations. The measurements are used to record the punctual microclimate conditions and to validate the simulation model of the current campus layout. Validation is defined as the process of determining if a computational simulation represents the real world and how accurately the computational results compare with experimental data [14, 15]. For the numerical simulation, the widely applied three-dimensional non-hydrostatic model for surface-plant-air interaction ENVI-met v. 4.4 is used [16].

2.1. Field measurements

The on-site field survey consisted of two parts: continuous meteorological measurements at a weather station and mobile infrared (IR) thermography. The meteorological measurements are obtained from a weather station which is located on the roof of the ZEB Test Cell Laboratory (TCL), south of the study area, see Figure 1. The weather station records air temperature, relative humidity, global horizontal radiation, wind speed and wind direction in one-minute intervals. The data is then compiled into one-hour averages to serve as validation input in the simulation model.

Surface temperature measurements were derived using an infrared camera (FLIR E60). The IR measurements were taken during calm, clear-sky conditions on the morning of 11 April 2019. The ambient temperature that day ranged from a low -1 °C to a high $+3$ °C. The IR camera is able to operate in a temperature range between -20 °C to $+120$ °C and has an accuracy of ± 2 °C or ± 2 % of reading for an ambient temperature between 10 °C and 35 °C [17]. The surface temperature of the most representative buildings for each category (see Table 1) and ground surface temperatures have been measured (see Figure 3). For the validation process, the five groups of buildings (*A1*, *A2*, *B1*, *B2*, *B3*) were sub-categorised based on the main characteristics such as the main orientation, the surroundings, the presence of trees, and the closeness and size of the plants. For each sub-category, a reference building was chosen to be analysed specifically (see Figure 4).

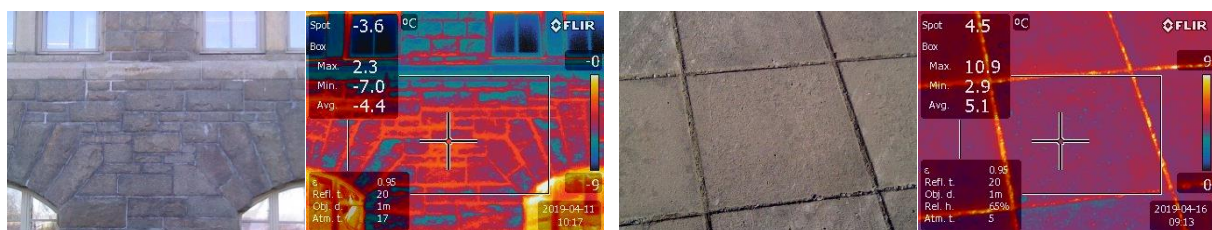


Figure 3. IR measurements of a building surface with granite stone (left) and concrete pavement (right).

2.2. Study area

Trondheim is Norway's third largest city by population with close to 200 000 inhabitants and is located at a 130 km long and 10–20 km wide fjord in Central Norway. The location's climate is subarctic (Dfc) according to the Köppen-Geiger classification system [18]. The 0.23 km² Gløshaugen campus of NTNU is located about 2 km south of Trondheim's city centre on a hill plateau (see Figure 1). In order to reduce the simulation time, a smaller portion of the campus (0.10 km²) was selected. This decision is supported by the fact that the main areas for people are also located in this smaller subarea (see Figure 2). This part has a relatively uniform elevation of about 47 m above mean sea level.

The mean annual temperature of Trondheim's official weather station in Voll is 4.8 °C. The average annual precipitation is 855 mm and the prevailing wind direction is south west (225°). As the official weather station is not in the vicinity of the campus, meteorological recordings from the ZEB TCL, located 400 m south of the study area, are used (see Figure 1 and Figure 2).

2.3. Model and computational domain

Aerial photographs from the Norwegian Mapping Authority (www.kartverket.no) were used to determine the positions of the different surface and vegetation cover types in the 3D model. Figure 4

shows the ENVI-met simulation model with view from the south. On-site inspections on the measurement date provided specific characteristics of the buildings, materials, and vegetation (including species) and confirmed that the information from the aerial photographs was up to date.

The grid of the calculation domain has dimensions of 416(x)_400(y)_94.5(z) metres and consists of 104_100_32 cells at each axis respectively. The lowest grid cell is split into five sub-cells with 0.6 m height each. Concerning the interference coming from boundaries to the flow and for the flow to develop, the distance between the objects and the domain boundaries was arranged based on ENVI-met specifications. For that, the height of the domain was modelled more than two times the highest building (Central Buildings' height: 45 m) and the horizontal distance to the model boundaries was at least equal to the closest building's height. In addition, four nesting grids were added around the core of the 3D model. For turbulence closure, ENVI-met uses the Mellor-Yamada turbulence model from 1982 [19].

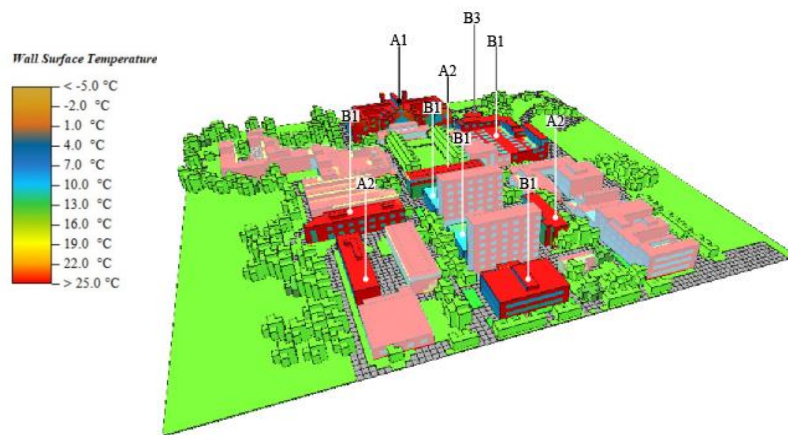


Figure 4. View of the ENVI-met simulation model from the south. The reference buildings for each category are indicated in brighter colours and are representative of sub-categories based on different conditions of orientation and surroundings.

2.3.1. Soils and surfaces. Three different surface types predominate in the area of interest. This includes the basic soil type and sealed surfaces like streets and pavements. Soil maps of the region showed that the model area's soil is mainly characterised by its clay content [20]. The remaining areas of the domain which are not covered by vegetation or buildings are impermeable surfaces. They were modelled based on the ENVI-met standard library values (surface albedo, aerodynamic roughness length, emissivity) for *Asphalt Road* and *Pavement (Concrete), used/dirty* [21].

2.3.2. Vegetation. Gløshaugen campus is embedded within a park-like environment and features green spaces and a great number of trees, shrubs and hedges throughout the area. For simplification purposes, vegetation types were limited to six different types of trees (of only three species), two hedge types, and one grass type. The existing vegetation from the program database has been scaled to fit the plant sizes on campus. Following tree species were modelled: *Norway Maple* (10, 15 and 20 m), *Larch* (20 m) and *Scots Pine* (5 and 10 m). The two hedge-types were 1 m high (one modelled as a conifer, one as deciduous) and the grass height was set to 0.1 m. The deciduous trees were assigned an annual schedule to regulate the leaf area density (LAD) according to the seasonality of foliage.

2.3.3. Buildings. The buildings at the campus were grouped into five categories (see Figure 2; Table 1) according to the wall's outermost thermally relevant material layer: stone, brick, concrete, glass and wood. Most of the buildings were built with concrete as an external wall material, followed by brick and wood. It is worth noting that the wooden buildings are rather small and situated on the north-eastern and north-western side of the campus. Moreover, for some of the buildings, glass is the main material for both walls and roofs (*Elektro* buildings). The roof materials were identified for each category. The properties of the materials used in the ENVI-met model are the default ones for concrete and glass, while for granite stone, solid brick and wood, new material database entries were created. All the materials have an emissivity of 0.90 except for the wood (0.86).

Table 1. Categories of the buildings in the ENVI-met model.

Category	Year of construction	Wall material	Roof Material
A1	1900-1950	Stone: granite	Wood: spruce
A2	1900-1950	Solid brick	Wood: spruce
B1	1951-2000	Concrete: filled blocks	Concrete: default
B2	1951-2000	Glass: clear float	Glass: clear float
B3	1951-2000	Wood: spruce	Wood: spruce

2.4. Boundary conditions

For the evaluation of the microclimatic conditions, simulations were performed for four days: 21 March (vernal equinox), 21 June (summer solstice), 23 September (autumnal equinox) and 21 December (winter solstice). The boundary conditions of the model are based on the records of the year 2018 from the weather station on campus. The hourly values of air temperature and relative humidity, the mean daily wind speed and the prevailing SW (225°) wind direction for Trondheim, were applied (Table 2). As the program does not allow for incorporating snow covered surfaces, freezing or thawing of water, the same surface properties and physical conditions for all simulated dates were used [22].

Table 2. Boundary conditions and statistical meteorological values of the simulated days during simulation time (T_{\min} , T_{\max} = temperature min./max. and time of occurrence in local standard time (LST); \bar{v}_w = mean wind speed; $\bar{\phi}$ = mean relative humidity; t_{sr} = LST of sunrise; t_{ss} = LST of sunset; $t_{sim,s}$ = LST of simulation start; $t_{sim,e}$ = LST of simulation end; $t_{sim,tot}$ = total time of simulation).

	T_{\min} (LST) [°C]	T_{\max} (LST) [°C]	\bar{v}_w [m/s]	$\bar{\phi}$ [%]	t_{sr} (LST)	t_{ss} (LST)	$t_{sim,s}$ (LST)	$t_{sim,e}$ (LST)	$t_{sim,tot}$ [h]
21.03.	2.6 (05:00)	4.2 (16:00)	1.7	85.1	6:17	18:35	6:00	19:00	13.0
21.06.	8.3 (06:00)	12.2 (18:00)	1.8	73.5	03:02	23:37	03:00	24:00	21.0
23.09.	5.5 (19:00)	8.0 (15:00)	2.5	77.7	07:03	19:16	07:00	20:00	13.0
21.12.	0.2 (06:00)	0.9 (12:00)	2.6	55.0	10:01	14:31	06:00	15:00	9.0

3. Results and discussion

3.1. Validation

The obtained data from the field measurements of the reference buildings were used to validate the results derived from the ENVI-met simulation from 10 April at 20:00 to 11 April at 13:00. The average difference between measured and simulated surface temperatures of the thirty measurement points was 4.9 K. However, ENVI-met presents a tendency to overestimate the surface temperature values, where IR-measured values were below or close to 0 °C (see Figure 5, eight values in total). For those values, the simulations surpassed the IR measurements by 7.9 K on average. The average deviation from the measurements of all other validation points was 2.8 K.

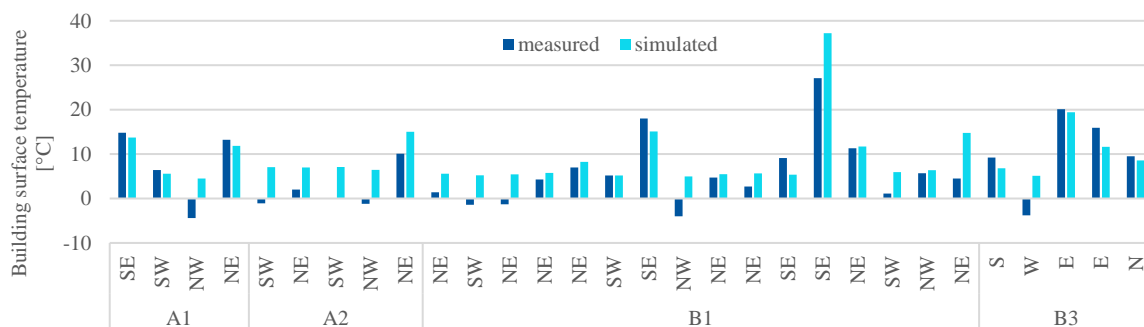


Figure 5. Measured (IR) and simulated building surface temperatures of the building categories on 11 April for different orientations.

Apart from the larger deviations at low temperatures, the magnitude of error is scattered arbitrary across the measurement points. Therefore, no systematic error for example regarding orientation, surface material, closeness to vegetation or point in time could be identified.

3.2. Microclimate analysis

Figure 6 illustrates the simulated air temperature field at 1.5 m height (pedestrian level). The unshaded south and west-facing surfaces get heated up by the exposure to solar radiation the most. Therefore, areas close to those surfaces show the highest air temperatures at pedestrian level. Especially the inner corner in the north west of the campus, where wind speeds are particularly low, represents a hot spot throughout the year, except for winter. The simulated values of air temperature correlate to the different surface types (albedo, emissivity) together with the wind field pattern and solar access. The materials with high heat storage capacity (i.e. asphalt, concrete pavement) present higher air temperatures than the vegetated areas.

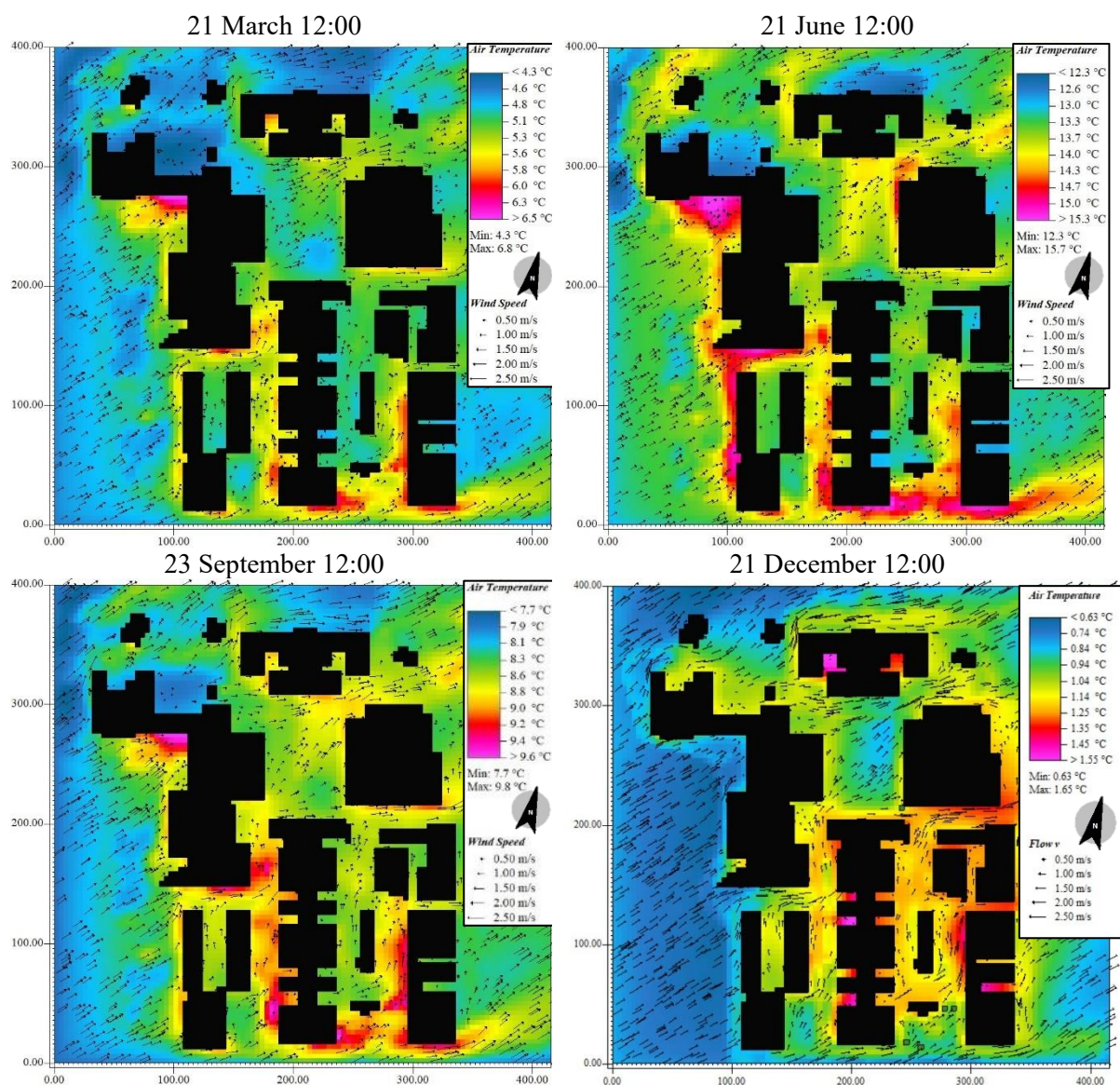


Figure 6. Air temperature and wind field at 12:00 at pedestrian level (1.5 m above ground) for the four simulated days.

In the colour map of 21 December, the grassed areas behind the main building (*C*), east of the cafeteria (*A*) and the smaller patch west of the cafeteria are recognisable in terms of contrasting colour. On the contrary, the paved and asphalted surfaces around the central buildings (*2a*, *2b*), and south of the VATL (*5*) show the highest temperatures. The cooler patches east of the central buildings are the areas where hedges and trees lead to lower air temperatures. The grassed areas surrounding the campus are generally cooler all year round and with exception of 21 December, the asphalted areas north of the main building (*3*) and north of the *Elektro* building represent the cold spots.

The highest absolute temperature difference (ATD) within the study area was simulated on 21 June with 3.4 K between the coolest and warmest spot. On 21 December on the other hand, it is lowest with only 1.2 K. The vernal and autumnal equinoxes have an ATD of 2.5 K and 2.1 K respectively. It is supposed that the ATD is mainly influenced by the amount of solar radiation reaching the surfaces.

Regarding the wind field, the input data for the wind speed varied between the simulated dates. However, the prevailing wind direction (225°) was kept the same. Thus, in this study, the proportional relation of local wind speeds to the undisturbed reference inflow at the same height level is of higher interest than absolute values. The resulting so-called wind speed change (WSC) showed only minor differences between the simulated dates. The maximum value for the WSC was lowest for the vernal equinox (138.0 %) and highest for the winter solstice (157.1 %). Summer solstice and autumnal equinox had a maximum WSC of 140.5 % and 152.0 % respectively.

On all the simulated dates, the south east corner of the campus (*Berg*-building) showed the highest WSC values. The southern part of the study area is close to the boundaries of the model, so even if it is an equally densely built-up area, the simulated results for this location present higher values due to the fact that the model considers there an undisturbed approaching flow. Furthermore, the simulation results indicate windy conditions at east-west passages. Those areas are for example the passage east of central building 2 (*2b*), south of the VATL (*5*), and between the main building (*3*) and the VATL. Additionally, the passage between the main building (*3*) and the small wooden building in the north west exhibits a high WSC with values close to the maximum on all simulated dates. The influence of the seasonal changing LAD of the vegetation had a visible but minor influence on WSC, especially in the tree-lined patch of grass behind the main building (*C*). The lowest wind speeds occurred in the wake of the larger buildings and especially in the small backyards south of the main building (*3*) and east of the central buildings (*2a*, *2b*).

4. Conclusion

In this study, the simulation tool ENVI-met was used for analysing the microclimatic conditions at a university campus in Trondheim, Norway. The analysis focused particularly on local air temperatures and the wind field at pedestrian level. The validation revealed an average difference of 4.9 K between the measured and the simulated building surface temperatures. However, ENVI-met tended to overestimate the low surface temperatures, especially where IR-measured values were below or very close to 0 °C.

The simulated values of air temperature correlate to the different surface types (albedo, emissivity) together with the wind field pattern and solar access. The materials with high heat storage capacity (i.e. asphalt, concrete pavement) present higher air temperatures than the vegetated areas.

The areas in front of south-facing and sunlit surfaces presented elevated local air temperature values. On 21 December, when almost no solar radiation is reaching the area due to very short days and low solar angles, the influence of the surface materials becomes more evident. At this time of the year, vegetated surfaces cause lower air temperatures at pedestrian level compared to heavier materials like concrete and asphalt. The highest ATD occurred on 21 June with 3.4 K between the warmest and coolest spot, the lowest on 21 December with 1.2 K.

The analysis of wind speed change identified east-west passages on campus as problematic. There, local wind speeds exceeded the reference wind speed at the inlet by up to 57.1 %. On the other hand, the lowest wind speed values occurred in the wake of the larger buildings and in particular in the small backyards south of the main building and on the east side of the central buildings.

The model has limitations as to the coarse grid resolution and the uniform discretisation, as the software does not allow refinements. Notably, the regular grid structure that does not admit of transverse, sloped or curved geometries, resulting in inaccuracies of simulated air flows. Additionally, the program does not allow for considering snow covered surfaces [22], which especially in December and March can have significant influence on physical properties and thus the microclimatic conditions [23]. However, the model can be of advantage and informative at the early stage of microclimate assessments.

In the future, a more comprehensive study will be conducted by using sophisticated computational fluid dynamics programs that allow a finer and more demand-actuated discretisation. The results of this study, in combination with a specific validation process for the air flows, will further deepen the knowledge of the microclimatic situation on the NTNU campus. This knowledge can then be applied in the planning of the campus' redevelopment, for instance to decide on where to plant new vegetation, which surface materials to use or where new buildings decrease the potential for natural ventilation.

5. Acknowledgements

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