A GIS-based model of outdoor thermal comfort: Case study for Zurich

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ABSTRACT

The importance of walking, the most basic form of transportation, is growing. Climate change, comfortable walking distances could get reduced drastically. There is a clear need to better understand how outdoor thermal comfort (OTC) and walking interact. In this work, thermoregulation of the human body is modeled with the two-node model to determine the influence of the microclimate on pedestrian's OTC. First, the impact of the current microclimate in Zurich on the route choice of pedestrians is analyzed. We found no significant correlation between simulated OTC of walking a particular route and route choices for all trips, but results for longer trips indicate a possible influence. It is pointed out that the same assessment could be done for other regions, and results could contribute to more accurate pedestrian modeling. Second, a tool is developed that can estimate OTC-corrected walking distances from any location. The tool is applied to the current climate and future climate scenarios. The results show that in the future, pedestrian's OTC in Zurich will be severely decreased. Further, the tool can detect where there is potential for and, through its accessibility approach, quantify improvements to the built environment citywide. Future work should focus on enhancing physiological input parameters to the model. This work provides a novel use of the two-node model for walking subjects in a citywide assessment.

Keywords: Outdoor Thermal Comfort, Heat Stress, Walkability, Route Choice, Dynamic Thermal Environment, Climate Change

INTRODUCTION

With the revival and reurbanization of the inner cities around the globe, walking, the most basic form of transportation, has become a topic of growing interest over the last decade. For certain use cases, walking can be considered superior to other modes, as it does not come with negative externalities regarding emissions, landscape aesthetics, and space consumption (1). It further includes positive externalities on the individual level such as physical and mental health (2) and can provide recreational value. For urban and transport planners, it is essential to know how to assess whether our cities are walkable and where improvements should be targeted. Following Sim (3), walkability can be defined as being "about accommodating walking, making it easy, efficient, and enjoyable." The walkability topic has been extensively addressed by literature (4, 5, 6, 7, 8, 9). Walkability is for instance enhanced by land-use diversity and density, nearby green areas, and less traffic. Reflecting on the existing research, one aspect which is often neglected when measuring walkability is the OTC of the pedestrian. While walkability comprises the influence on the quality, the term of accessibility stands for the quantitative number of opportunities (10). Low OTC can restrict walkability and accessibility. Evaluating OTC becomes of growing importance in the face of the global climate crisis. The official Swiss Climate Change Scenarios (11), indicate potential temperature increases in the summer months of 6°C for 2060 under the RCP8.5 scenario. Many studies have modeled OTC for a steady state of walking activities and environmental conditions (e.g. (12)). The results are typically maps that indicate which places are comfortable and which not (13). However, none of the existing research has connected OTC, measured with dynamic environmental states that are mapped to the spatio-temporal dimension of a given pedestrian trajectory, to the concept of walkability or accessibility.

This paper focuses on the dynamics of OTC for pedestrians in the City of Zurich, Switzerland. In a first step, we set up a data processing pipeline allowing us to estimate the OTC employing the thermoregulatory model from Melnikov et al. (14). We then conduct a descriptive analysis using real-world GPS pedestrian tracks to investigate how OTC affects the route choice in an urban environment. Finally, we present an OTC-corrected accessibility planning tool that uses an OTC-corrected routing engine to predict how far pedestrians can walk comfortably facing current and predicted temperature conditions. The remaining paper is structured as follows: Section 2 provides the theoretical foundation of the human thermoregulatory system (HTS), OTC assessment, and findings on pedestrian route choice. We then present the methodology in Section 3. Section 4 presents the results for the descriptive route choice, Section 5 for the OTC-corrected accessibility planning. Section 6 discusses and concludes the results.

RELATED WORK

Human Thermoregulation & the Two-Node Model

In this work, we model the HTS with Melnikov et al. (14) implementation of Gagge's two-node model (TNM) (15). In the TNM, the human body is divided into two concentric shells, the interior core with uniform T_{cr} and the outer skin shell with uniform T_{sk}. Heat transfer is realized between these two layers and between the outer shell and the environment. The human body aims to maintain T_{cr} and T_{sk} steady and can initiate different thermoregulatory control functions to do so. If and how much T_{cr} and T_{sk} deviate from target values is determined by the human heat balance. The body tries to reach a stable state where the heat storage rate (St) is $St = H_p - H_l \approx 0$. Both the produced (H_p) and lost heat (H_l) are influenced by the individual's characteristics, such as weight and height, clothing, and especially by the surrounding microclimate. Heat is produced as a result

of metabolic activity (M), which is not used for mechanical work WR, and through shivering (S_h) in cold temperatures. The heat production is then $H_p = M - WR + S_h$ (16). Heat lost by convection C (from the skin to the air) and radiative heat exchange R with surfaces in the environment, through respiration Re (warming and moisturizing inhaled air), and through evaporation of sweat E. The heat loss rate is hence $H_l = C + R + E + R_e$ (16).

Skin Wettedness

The existing literature reveals that in cold environments, thermal discomfort has a high correlation with skin surface temperature. In hot environments or while exercising, it is more related to sweating (17, 18). The sweat produced to keep the HTS in balance evaporates. The share of skin surface needed to evaporate the produced sweat is called skin wettedness (wt) (18). It is a dimensionless variable with a minimum value equal to 0.06 because of the moisture diffusion happening through the skin and a maximum of 1 when sweat covers the entire skin surface (18). Nishi and Gagge (18) found that metabolism due to exercise determines the thermal comfort (TC) limit, resulting in a wt threshold (wt_{thr}) defined as:

$$wt_{thr} = 0.0012M + 0.15 \quad (1)$$

with M in W/m^2. Fukazawa and Havenith (17) confirmed this relation with a study for garment design on differences in comfort perception while walking at 4.5 km/h. Also, the results of Lee et al. (19) with eight male Japanese subjects walking between 6-8 km/h and the work of Vargas et al. (20) with 16 young adults from the US found that the discomfort level follows the relation proposed by Nishi and Gagge. In general, when studies assess walking subjects, the M-dependent threshold from Nishi and Gagge (18) is used or referred to.

Pedestrian OTC Assessment

OTC can be defined as "the condition of mind that expresses satisfaction with the outdoor thermal environment" (21). There are several metrics to assess OTC, which are based on the TNM. The most widely used is the physiologically equivalent temperature (PET) (22). An important feature of this index is that it provides a "feels-like" temperature allowing to compare the effect of the microclimate on the thermophysiological state of a person. Further, it considers a steady physiological state, which is reasonable for indoor conditions but barely the case for outdoor environments due to the significant variance of microclimate conditions and the diverse activities people perform. This is why thermal history, dynamic exposure, and the activity of a person are critically important to assess instantaneous and dynamic thermophysiological states. Existing studies using the PET differ significantly regarding their results on comfortable temperature ranges because they lack the just mentioned aspects (23). Some scientists extended the TNM to overcome these fundamental limitations. Lai et al. (23) "developed a human heat transfer model that considers outdoor radiative heat exchange and transient heat transfer in clothing." Their overall results were satisfying, but during hot conditions, skin temperature prediction error was up to 6°C. An extension of Gagge's TNM that is validated for the wide range of warm thermal environments is provided by Melnikov et al. (14). With their modified model for skin blood flow, they accurately predicted skin temperature in unsteady conditions for measured data on 15 subjects.

Pedestrian Route Choice

Pedestrian route choice has been studied by scholars from different sectors like public health, real estate, pedestrian interaction modeling, designing of pedestrian infrastructure. From a perspective of urban- and transport planning, this paper aims to understand how the micro-built environment affects walking route choice to improve this built environment. Existing studies are either based on stated (SP) and revealed preference (RP), whereas the latter is considered to provide a better representation of real-world behavior (6). Numerous studies show that trip length is the primary determinant to chose a particular route (6). Broach and Dill (5) used 1,167 GPS tracks realized by 283 adults (avg. trip length was 875 m) and compared several route attributes with those of possible alternatives. They found that higher traffic (+14%), missing crossing infrastructure (+73% for major roads), and primarily steep uphill gradients (+99%) increase perceived walking time. Neighborhood commercial reduced the perceived walking time by (-28%). Guo (4) observed subway egress trips and found that steepness and parks have a high effect on utility, while sidewalk width, intersection density, and neighborhood businesses only have a minor influence. Erath et al. (8) estimated elasticities for walking time-based on SP and RP data. Amongst other variables, they found that active window frontage (-17.5%) and relevant greenery reduce perceived walking time (-23%). A recent study from Salazar Miranda et al. (9) using GPS tracks found that pedestrians systematically deviate from their shortest path. They do so to walk on streets close to parks, have more business establishments, and have urban furniture.

If humans cannot cope with the stress caused by the microclimate and the physiological responses, they must adapt their behavior (24). Several studies confirm that pedestrians incorporate behavioral adjustments to maintain their HTS in balance. Lee (25) found that not T_{air} but global radiation (GR) from the sunlight, which determines mean radiant temperature (T_{mrt}), was the reason for people changing the side of the street in a study on four locations in New York City. A recent study from Singapore (24) examined the effect of shade on path choice. They found that pedestrians' assumed walking time in the sun was 16% higher than on a shaded path.

METHODOLOGY

Estimation of the Microclimate Conditions

According to various studies, T_{mrt} (average temperature of the surfaces that surround a person, with which the person exchanges thermal radiation) is the driving parameter of human OTC (26) as T_{mrt} determines the level of radiative heat exchange and varies significantly. Other variables (e.g., T_{air}, RH) are steadier in urban environments; thus, there is less chance of them affecting the dynamics of HTS (16). T_{mrt} is calculated with the Solar Long Wave Environmental Irradiance Geometry model (SOLWEIG) (27). The SOLWEIG model is part of the Urban Multi-scale Environmental Predictor (UMEP), a tool that combines models essential for climate simulations (27). Due to its 3D approach and high level of detail, it can contemplate complex urban situations. Several studies confirmed the ability of the SOLWEIG tool to predict T_{mrt} in different places and often better than its competitor Softwares RayMan Pro or ENVI-met (27, 26). SOLWEIG requires inputs such as digital elevation models, land cover information, sky view factor (fraction of sky which can be seen from a given place), meteorological data, and albedo-, emissivity- and absorption-factors of different materials, all of which are accessible through open data or can be calculated with UMEP's preprocessors. From all these, the meteorological data represent the essential input for SOLWEIG, and their derivation required extensive data processing and computation. For the air temperature T_{air} and relative humidity RH, the study area is segmented into a 100x100m grid resulting in 5,714

patches, i.e. microclimate zones. T_{air} and RH are averaged from the three closest out of 28 weather stations, weighted by their inverse Euclidean distance. T_{air} is corrected for altitude differences with a vertical temperature gradient of 0.62°C per 100 m (28) due to the hilly topology of Zurich. The global radiation GR is only measured through one sensor for Zurich and hence set constant for all microclimate zones. For the final T_{mrt} calculation, all input data apart from the microclimate zones are aggregated to 2.5x2.5m to keep computation manageable. An example of the result is shown in Section 4.1.

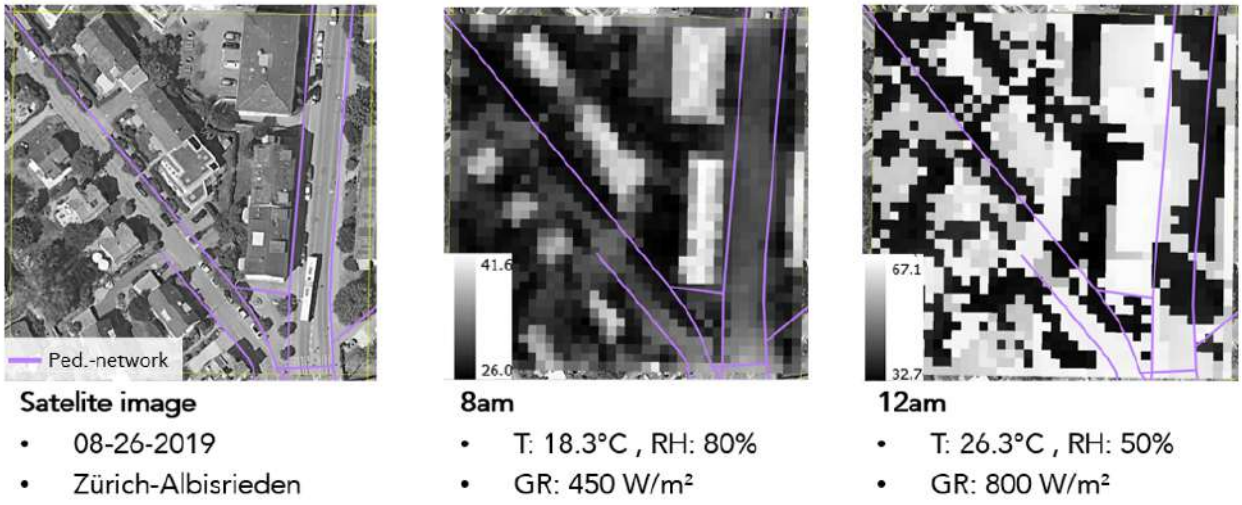

FIGURE 1: Mean Radiant Temperature on a 2.5x2.5m resolution for an example location for 8am and 12am, basemap: (29)

Model for metabolic and mechanical work rate

Metabolic and mechanical work rates are essential variables in the human heat balance. M and WR influence the level of heat gains. While there are simulations considering level walking (23, 14, 30), the gradient of the walking surface, which dramatically affects M and W, was not previously integrated in simulations of pedestrian heat stress. We use equation 1 adapted from Ardigò et al. (31) to estimate the metabolic rate M of walking:

$$C_w = 1.866av^2 - 3.773bv + c + 4.456 \quad [J \cdot kg^{-1} \cdot m^{-1}] \tag{2}$$

where $a = e^{4.911i}, b = e^{3.416i}, c = 45.72i^2 + 18.9i$, with i being the gradient in % and v is speed in m/s and add the resting metabolic cost from Since Ardigó *et al.*'s formula only accounts for the walking part of metabolic cost (M_{base}), of 1.00108 $[W \cdot kg^{-1}]$ (32) to C_w.

The mechanical work WR for walking can be divided into two parts: 1. external work (WR_{ext}) "necessary to sustain the displacement of the center of mass of the body (COM) relative to the surroundings", 2. internal work (WR_{int}) "done to move the limbs relative to the COM" and "work done by the trailing limb against the leading limb during double support" (33). We developed a new model to estimate speed and gradient dependent WR based on two studies. Values for WR_{int} are taken from Minetti et al. (34) and WR_{ext} is provided by the study of Dewolf et al. (33).

Their data points are fitted separately with polynomial regressions, and then they are summed up.

Both mechanical work rate and metabolic rate for walking speeds considered in this research are shown in Section 4.2.

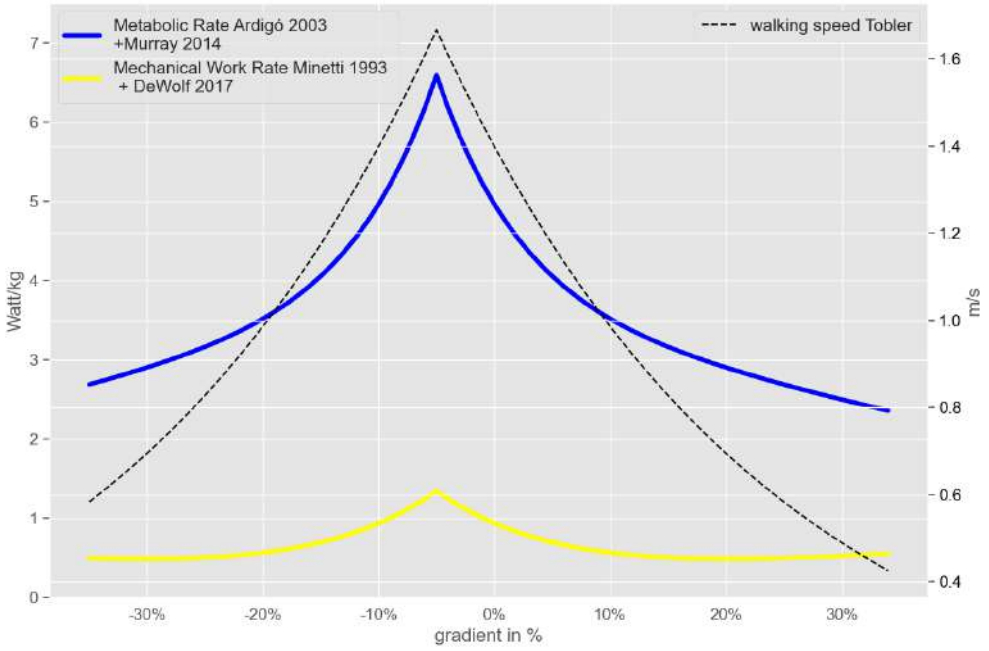

FIGURE 2: Estimated model of metabolic rate and mechanical work rate for different gradient-walking speed pairs

Pedestrian Route Choice

Network and Enrichment

OSMnx is used to create a routable network from the pedestrian network provided by the City of Zurich. The pedestrian network used is composed of 54,608 edges and 17,582 nodes. With the elevation data sourced from the Google API (29) the gradient of each edge is calculated. The network is enriched with several attributes which have been identified as relevant from the literature (see: Section 4.3.1). The built environment attributes are sourced from OpenStreetMap (OSM) and the City of Zurich. The attributes include 4,639 business establishments (containing shops and food and beverage facilities), 7,867 urban furniture elements (including benches, trash bins, drinking water fountains, and public toilets), 73,042 trees (registered in the public cadaster), and neighboring parks and urban forests. All attributes are assigned to the corresponding edges of the pedestrian network if they are in a range of 10m. Furthermore, the network is enriched with the average weekday traffic (AAWT, in the following traffic), provided by (35) with around 60% network coverage. The traffic data contains the streets' centerline and is assigned to the edges using a 20m range. Finally, the share of conveniently walkable gradients that is conveniently walkable gradient is defined as -5% to 1% because of the ratio between *M* and *WR* rate, is encoded based on the network topology.

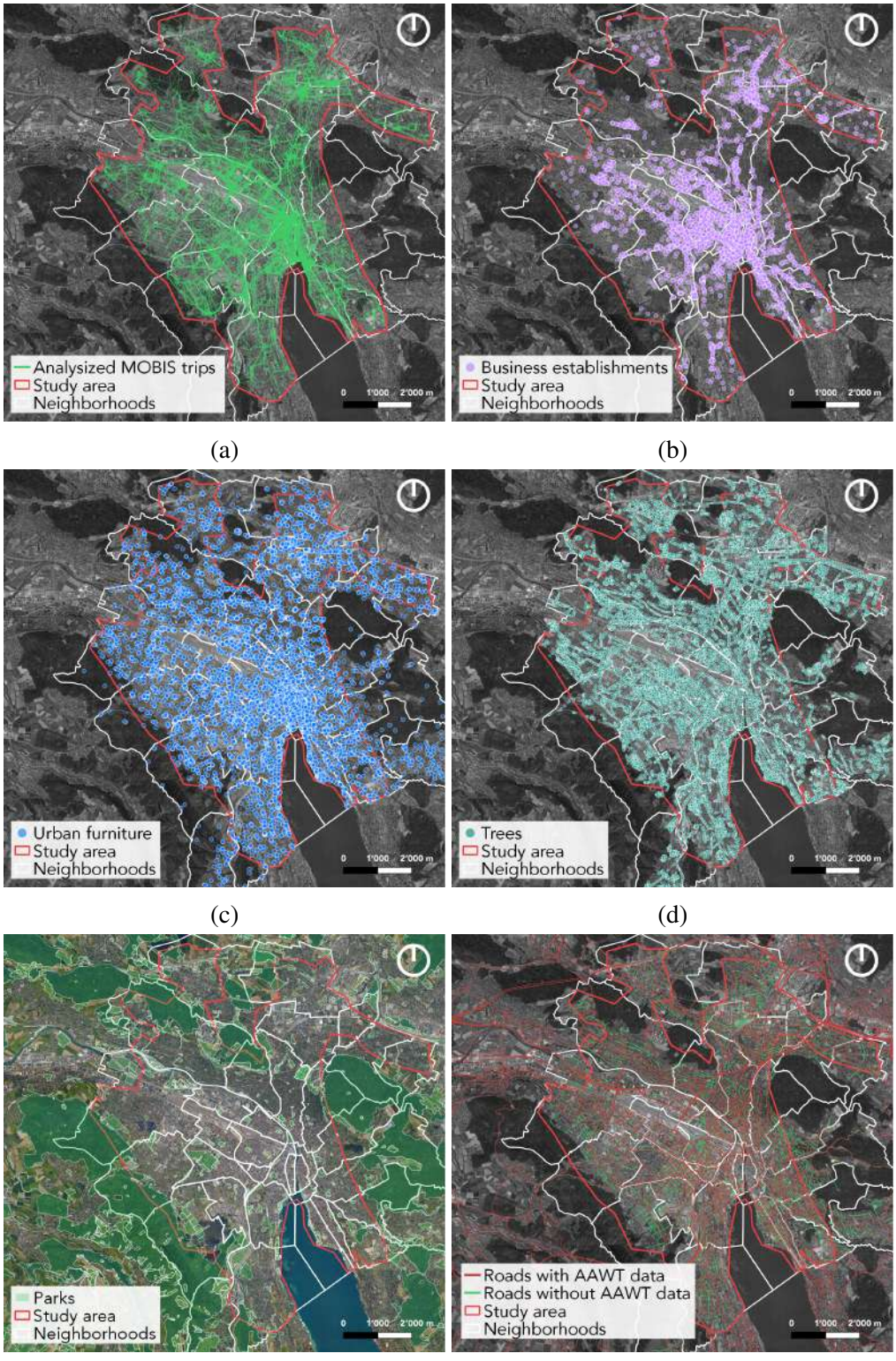

FIGURE 3: Study area (a), built environment attributes: business establishments (b), urban furniture (c), trees (d), parks and urban forests (e), and AAWT (f)

Pedestrian's Trajectory Data

The trajectory data used for this work comes from the MOBIS-covid project, an app-based GPS-tracking travel diary study (36). The built environment and OTC-related attributes of these trajectories are compared to the same attributes of the shortest path of the respective origin-destination pair. The study area does not contain the whole city of Zurich (see Section 4.3.1 (a)) but only the parts which contain the majority (94%) of the trajectories due to the computational constraints. The 70 warmest days in 2020 are selected for the analysis. For the 70 days, the microclimate is calculated between 8:00 AM and 8:00 PM in 90-minute steps due to computational capacity of the T_{mrt} calculation, resulting in nine points of time in a day and a total of 630 microclimates for each microclimate zone. Trips shorter than 200 m are removed because they are too short to obtain a satisfactory result on OTC in Zurich's climate. Moreover, paths where the start and endpoint are less than 200 m apart are sorted out because they are likely to be roundtrips. Hence the shortest path comparison would yield misleading results. The remaining trips are matched to the pedestrian network, using a Hidden Markov Model-based map matching framework from Meert and Verbeke (37). Then, the microclimate zones (100x100m) and the T_{mrt} cells (2.5x2.5m) are assigned to the trips based on time and location. In many cases, trajectories lie in more than one microclimate zone or T_{mrt} cell. In this case, the trajectory is cut, and each part of the segment is assigned to its corresponding microclimate zone and T_{mrt} cell. To not further increase computation times, the wind data is mapped on each trajectory segment's centroid. The final sample of trajectories contains 2'660 trips, realized by 333 different individuals, of which 59% are female, with an average age of 43 years. To initialize the thermoregulatory model, average weight and height for gender-age pairs of the participants are determined from the national health survey 2017 (38). The clothing level I_{CL} is estimated through the linear function $I_{CL} = 1.625 - 0.0375T_{air}$, obtained from Melnikov et al. (30).

OTC-Corrected Accessibility Planning

Implementation of the Tool

The developed tool enables users to calculate the OTC-corrected maximum walking area from every given point in the city. Also, here the pedestrian network of the City of Zurich is used, but the maximum edge length is set to 30m to get more accurate results. To calculate the isochrones from each point of interest, the shortest paths are calculated to all other nodes in the network, reachable in a defined walking time. The walking speed is assumed to be gradient-dependent, defined by Tobler's hiking function (39). The assignment of the microclimate to the network and the clothing are done in the same way as described in Section 4.3. Additionally, it is assumed that T_{mrt} is equal to T_{air} if the edge is inside a building. The weight of the assessed individual is assumed to be 72.3kg and height 1.71m which represents the average Swiss citizen (38). The metabolic dependent wt threshold is calculated with Eq. (1). The trajectory's segments have an average length of just 2.8 m. M depends on speed and gradient, and they are different for every segment of the trajectory. The threshold would hence fluctuate a lot, and it would be unrealistic to assume that someone stops walking when the threshold wt_{thr} is reached for a fraction of the whole trip. Hence, it is decided to calculate the threshold based on the weighted mean of the edges from the ≈ 80 s. The paths are then cut when the threshold wt_{thr} is exceeded. The tool's code will be made available to interested colleagues on request.

Use Cases & Scenarios

The tool's usefulness is demonstrated by evaluating two of the municipality's community centers for different climate scenarios. One community center (CC) is "Bäckeranlage," a dense urban district with relatively narrow street canyons. The other is "Oerlikon," selected because new developments on former industrial production sites representing contemporary common building practice are within a 20-minute walking radius. The area enclosing all comfortable reachable edges, and the number of persons living in this area within 20 minutes walking time is assessed.

The tool draws on estimating the thermoregulatory model and derivation microclimate zones from the previous route choice analysis. Scenarios Median and Hottest are based on the already computed microclimate for the 70 warmest days in 2020. As mentioned earlier, the number of hot days (> 30°C) and the average daily maximum temperatures are expected to increase drastically in the future. We hence additionally evaluate the climate scenarios under RCP4.5 and RCP8.5 for 2060. The mean daily maximum temperature increase in August from these scenarios (3.5°C for RCP4.5 and 5.6°C for RCP8.5) is added to the hottest measured temperature of 2020. The represented quantitative and qualitative evaluation focuses on the time of day with the highest solar radiation, and thus highest T_{mrt}, i.e., 12:30. The specific scenarios are as follows:

Scenario Median the median (50% higher, 50% lower), T_{air} at 12:30PM (09-09-20): 24.7°C
Scenario Hottest the hottest day, T_{air} at 12:30PM (11-08-20): 31.4°C
Scenario 2060 RCP4.5 the hottest day in 2060, considering scenario RCP 4.5 (11), T_{air} at 12:30 PM: 34.9°C
Scenario 2060 RCP8.5 the hottest day in 2060, considering scenario RCP 8.5 (11), T_{air} at 12:30 PM: 37.0°C

RESULTS ON ROUTE CHOICE OF MOBIS-COVID TRIPS

Thermal Comfort

Table 1 shows the comparison between the statistics of the chosen and shortest path. Mean T_{air} and T_{mrt} are almost identical. The average mean and maximum level of *wt* experienced during trips are higher for chosen paths. Also, the share of chosen paths with a higher mean and maximum *wt* was higher, which is not surprising: For the 70 warmest days that this paper is considering, the body must compensate for excess heat during almost the entire path (97.5%). Hence, *wt* increases steadily during a trip because the body's core and skin temperature increases steadily, making increased heat losses in the form of evaporation necessary (see Section 5.1). The chosen paths are an average of 89 seconds/123 meters longer, meaning that the body continues sweating during this surplus time with higher T_{cr} and T_{sk}, resulting in the higher mean and maximum *wt* value for chosen paths. The results in a subset with trips where the chosen path is less than 10% longer than the shortest path confirm the hypothesis that higher *wt* is due to longer trips. In these cases, the mean and median for both *wt* variables are almost identical, and no more significant differences can be revealed. The ranges of maximum *wt* are on a level that does not cause strong thermal discomfort, and the wt_{thr} threshold of 0.38 (M=190W/m^2, v=1.4m/s) is exceeded for only three trips. The short mean walking time (chosen paths: ∼nine minutes, shortest paths: ∼eight minutes) together with the temperatures present for the MOBIS-covid data (mean T_{air} is 25°C), leads to the conclusion that anticipation of level of thermal comfort is not considered by the participants in the process of route choice. This might be both due to relatively comfortable overall thermal conditions and smaller possible differences in thermal experience in such a short period. However,

TABLE 1: Overall results chosen path vs. shortest path: Compared are the mean, median, and standard deviation of the attributes for all trips. The share of chosen paths with a higher, the same, or lower value for the attribute than its corresponding shortest path is stated. The distribution of the attributes' means is- compared between chosen and shortest paths with two statistical tests.

	chosen path			shortest path			% of chosen value is ... than shortest		
attribute	mean	median	std.	mean	median	std.	>	=	<
mean skin wet.$^{*/\#}$	0.137	0.13	0.03	0.129	0.123	0.029	87.3	0	12.7
max skin wet.$^{*/\#}$	0.182	0.173	0.046	0.171	0.162	0.044	85.4	0.2	14.4
mean T_{air} in °C	25.14	25.30	3.50	25.14	25.3	3.496	48.5	3.5	47.9
mean T_{mrt} in °C	37.72	38.38	11.43	37.76	38.04	11.60	50.4	0	49.5
length in m$^{*/\#}$	756	603	504	633	503	431	98.5	0	1.4
time in s$^{*/\#}$	549	439	368	460	365	315	99.9	0	0
traffic	3,139	2,478	2,735	3,272	2,523	2,907	43.9	3.3	52.8
% of flat	74.6	81.7	24.8	74	81.4	26.2	50	10	39.9
no. busin./100 m	2.539	1.614	2.777	2.61	1.608	2.927	40	11.9	48.1
no. urb. furn./100 m*	1.036	0.791	0.926	0.992	0.727	0.944	43	6.7	50.3
% along park	12.4	0	20.4	11.9	0	20.4	21.6	52.8	25.6
no. trees/100 m$^{*/\#}$	2.878	2.316	2.707	2.78	2.132	2.752	43.9	10.2	45.9

n=2,061, chosen = shortest path: 598, 64.3% of the chosen route is different from shortest route, */#=significant on α=0.05 for Mann-Whitney-U-/Two-sample Kolmogorov–Smirnov-Test

TABLE 2: Results for longer trips: The mean value of each attribute is compared between chosen and shortest path for subsets of trips with different minimum lengths. Statistical tests are applied to compare the distribution of the mean for each attribute.

	>696 m (n=609)			>1,100 m (n=203)			>1,500 m (n=96)		
	mean		MWU/	mean		MWU/	mean		MWU/
	ch.	sh.	KS2S	ch.	sh.	KS2S	ch.	sh.	KS2S
mean skin wet.	0.166	0.159	*/#	0.193	0.185	*	0.209	0.202	
max skin wet.	0.226	0.216	*/#	0.261	0.252		0.282	0.276	
mean T_{air} in °C	25.20	25.19		25.23	25.24		24.79	24.80	
mean T_{mrt} in °C	36.87	37.04		38.15	38.50		39.39	40.07	
length in m	1,300	1,126	*/#	1,898	1,653	*/#	2,365	2,084	*/#
time in s	945	819	*/#	1,378	1,203	*/#	1,713	1,512	*/#
traffic	3,534	3,848	*	3,663	3,939		3,621	4,037	*/#
% of flat	72.8	71.7		69.3	68.1		68.6	68.3	
no. busin./100 m	1.987	2.013		1.478	1.666		1.387	1.506	
no. urb. furn./100 m	1.047	0.946	*	0.965	0.864		0.867	0.775	
% along park	17.1	15.8		18.3	16.6		17.0	15.8	
no. trees/100 m	3.382	3.054	*	3.528	3.034	*	3.787	3.269	*

ch. = chosen path, sh. = shortest path, */#=significant on α=0.05 for Mann-Whitney-U-(MWU) / Two-sample Kolmogorov–Smirnov-Test (KS2S)

the results in Table 2 indicate that for longer trips, thermal comfort might play an increasing role in the participant's route choice. Mean and maximum *wt* of chosen paths compared to shortest paths are becoming more similar the longer trips are. For trips longer than 1,500 m, the values of mean and maximum *wt* for both paths sets are almost equal, despite the more than three minutes longer walking time for chosen paths, where *wt* continues to increase steadily. Another indicator for a conscious OTC-seeking route choice behavior in the lower T_{mrt} for chosen paths compared to shortest paths, which gets higher with increasing trip lengths (by 0.17°C for trips>696 m, by 0.35°C for trips>1,100 m and by 0.68°C for trips>1,500 m).

Built Environment and General Observations

In general, participants of the MOBIS-covid study prefer longer paths for their trips, both in terms of length and travel time. Also, for only 22.5% of the trips, people chose the shortest path. For the trips where the chosen path is different from the shortest path, 64.3% of the chosen route's length is different from the shortest route meaning chosen paths are substantially different. In the overall results (see Table 1), all attributes of the built environment except business establishments have higher (respectively traffic lower) mean values for chosen paths when compared to the shortest ones. For the number of urban furniture (WMN) and trees, the distribution of the mean is significantly different (WMN&KS2S). Nevertheless, only for traffic and percentage of flat gradients, the chosen paths have a higher share of lower (for traffic) respectively higher values (for the percentage of flat gradients).

It was found that for longer trips, the built environment gains importance. In Table 2 it can

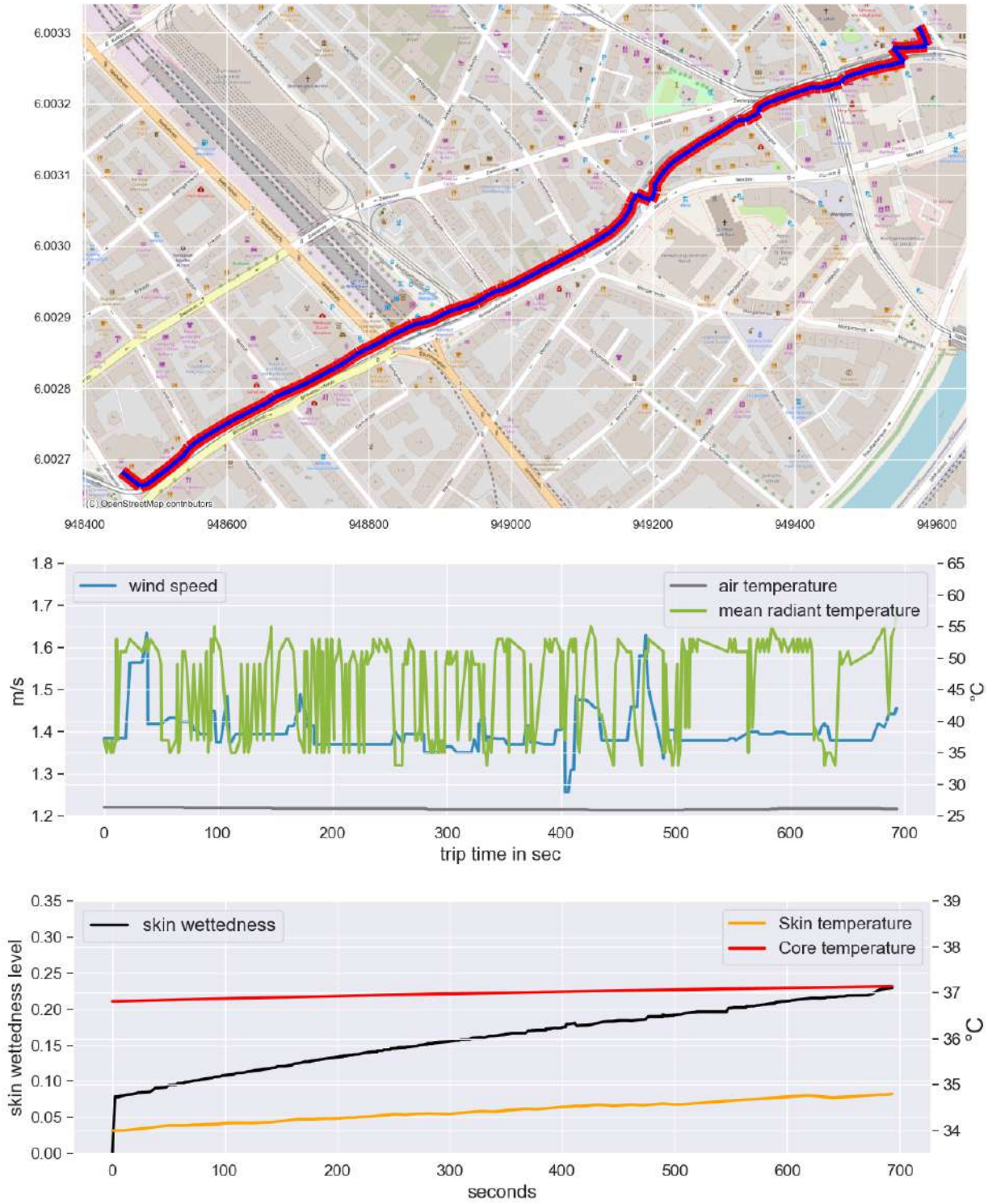

FIGURE 4: Exemplary path, top: Trajectory, center: Air- and mean radiant temperature, and wind speed; bottom: Skin wettedness, core- and skin temperature

be seen that the difference between the values of the attributes for chosen and shortest path get more pronounced for longer trips. For example, the traffic for chosen paths considering the overall results is approximately 100 vehicles/h less than for the shortest paths. At the same time, there are around 300 fewer vehicles/h for the subset of trips where the shortest path is longer than 696m. The same pattern can be observed for the other attributes, except for business establishments which are consistently higher for shortest paths, contrary to findings of previous studies. The share of chosen paths with higher (for traffic lower) mean values is higher for traffic, the percentage flat gradients, the number of trees, and urban furniture, when considering longer trips. For the percentage of trips along a park, the share of chosen paths with higher values is slightly lower. The mean number of trees, percentage of trip along parks, percentage of flat gradients, and traffic are higher than the overall results for longer trips. This can be explained by that the probability of passing by green areas and busier roads for longer trips is higher, and the likelihood for steeper gradients is higher for longer trips. The number of urban furniture and business establishments is lower because there are fewer businesses and urban furniture along green areas.

The analysis of the MOBIS-covid data showed that currently, OTC has a limited influence on route choice in Zurich. This is partly because an insufficient number of trips were done under temperatures that noticeably negatively affect OTC, and the length of the trips was short. This is confirmed by the results presented in Section 6, where it was found that the current climate has a weak influence on the OTC-corrected walking distance for trips up to 20 minutes. Nevertheless, longer trips showed that OTC could potentially play a role in the route choice, but the low samples-size (96) impedes secure conclusions. The designed methodology to assess OTC for the travel diary trips is novel, supporting that such estimation can be done with existing models and data, even on a citywide level. Regarding the built environment attributes, it was shown that these become more important for longer trips.

RESULTS ON OTC-CORRECTED ACCESSIBILITY

Table 3 shows the statistics for the different scenarios for the two community centers. For the median scenario, the area and population for both CCs are not affected at all (see Section 6). CC Bäckeranlage is almost unaffected by the hottest scenario. In contrast, CC Oerlikon shows some (minor) reductions for the area and population inside this area. Also, for the more moderate RCP4.5 scenario, reductions for Oerlikon are more pronounced: ca. 15% of the area is reduced, and population inside the area decreases by 13.4%. The losses are all located at the fringes of the walkable radius, which is intuitive because *wt* steadily increases in hot conditions. The decrease in the area (-10.6%) and population inside this area (-5.2%) for CC Bäckeranlage for the same scenario is smaller. In the RCP8.5 scenario for CC Oerlikon, the decrease of area (-42.7%) and population inside the area (-36.1%) is more pronounced. For the new urban developments, no striking differences compared to the rest of the urban fabric can be observed. Compared to CC Bäckeranlage, the comfortable walking paths are reduced spatially more uniformly. For CC Bäckeranlage, the area is reduced by over 50%, and the population inside the area decreases by almost 40%. This can be explained by the high building density and extensive impervious surfaces present, which is further confirmed with higher T_{air} (CC Bäckeranlage: 37.2°C, CC Oerlikon 36.5°C). The difference between scenario RCP4.5 and RCP8.5 for both CCs is notable because, in the RCP8.5 scenario, heat loss through convection is minimized due to warmer T_{air} than T_{sk} for many time steps. For some time steps, heat convects from the air to the human body. See Section 6 for an example trajectory. Increased sweat production tries to compensate for this, resulting in a

TABLE 3: Statistics on CC Bäckeranlage and CC Oerlikon

		area in km^2			population inside area		
		before	after	Δ	before	after	Δ
CC Bäckeranlage	**median**	5.08	5.08	0 (±0%)	59,421	59,421	0 (±0%)
	hottest	5.08	5.06	-0.02 (-0.3%)	59,421	59,421	0 (±0%)
	2060: RCP4.5	5.08	4.54	-0.54 (-10.6%)	59,421	56,342	-3,079 (-5.2%)
	2060: RCP8.5	5.08	2.26	-2.82 (-55.5%)	59,421	36,651	-22,770 (-38.3%)
CC Oerlikon	**median**	4.89	4.89	0 (±0%)	41,711	41,711	0 (±0%)
	hottest	4.89	4.71	-0.18 (-3.5%)	41,711	40,138	-1,573 (-3.8%)
	2060: RCP4.5	4.89	4.14	-0.75 (-15.3%)	41,711	36,141	-5,570 (-13.4%)
	2060: RCP8.5	4.89	2.8	-2.09 (-42.7%)	41,711	26,644	-15,067 (-36.1%)

faster exceeding of wt_{thr} limit. For both scenarios, radiation is negative (meaning that heat is not lost but gained by the body) because T_{mrt} is always higher than the body's skin temperature. Very high T_{mrt} values due to missing shading on big intersections before and on bridges lead to many paths ending at these places in the RCP8.5 scenario.

We demonstrated that OTC is not harmed under current climate conditions but will be reduced so severely in the context of future climate change that comfortable walking areas are diminished. The incorporation of shading in bridge design could significantly increase the range of thermally comfortable walks. The low *RH* in Zurich (ca. 40% for the hottest scenario), despite the high temperatures in the hottest scenario, helps efficient dissipation of heat through evaporation, explaining the small negative impact of the current climate on OTC. We simulated a hypothetical scenario of 75% relative humidity (typical for tropical cities like Singapore). The results reveal the significant impact of *RH* on comfortable walking (see Section 6). The reachable area is reduced by 80% and the population inside this area by 70%. This represents more significant decreases than the 2060 RCP8.5 scenario and can be explained by the reduced possibility of losing heat through evaporation.

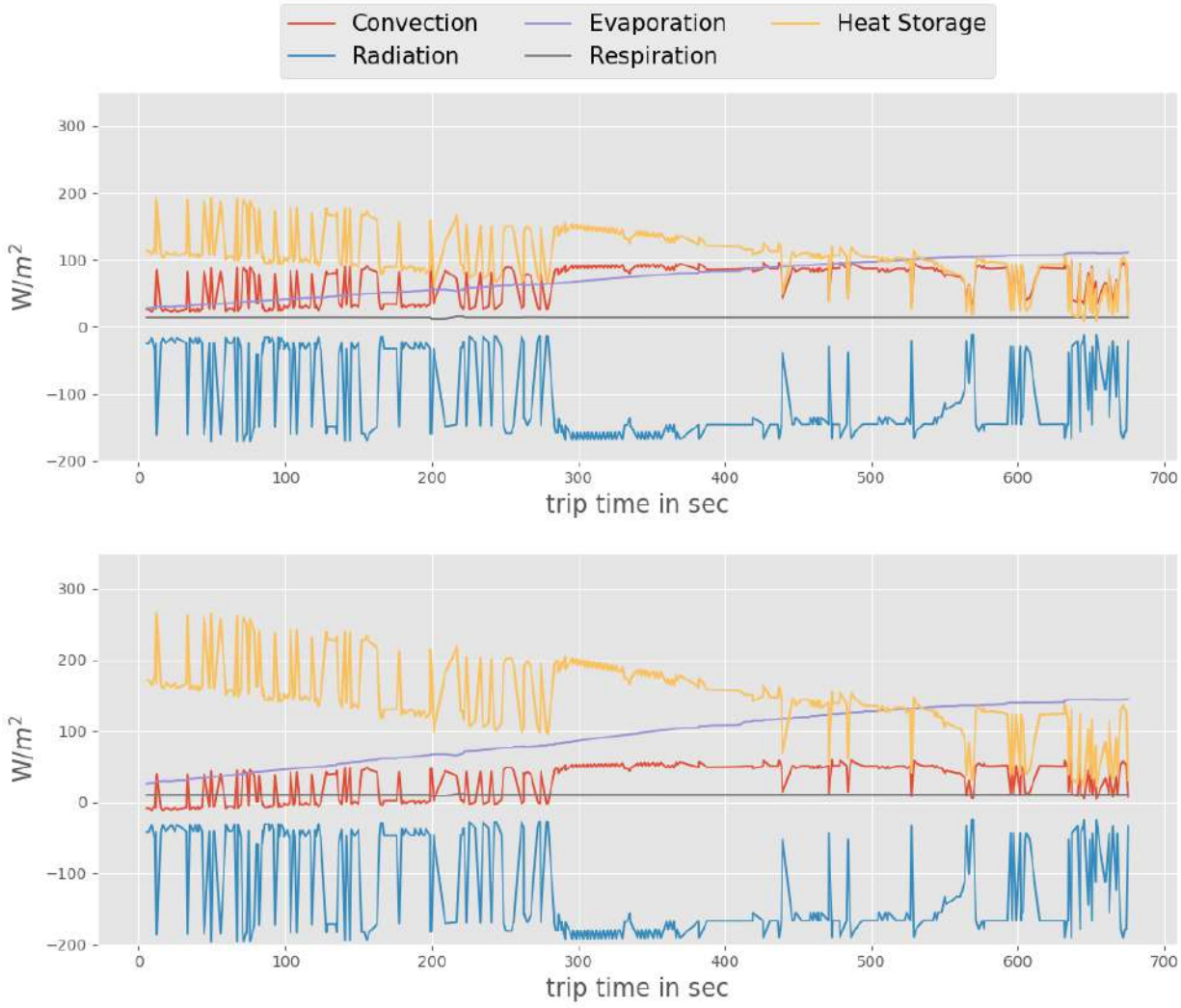

FIGURE 5: Human heat balance for an exemplary path (without *M* and *WR*), top: scenario hottest, bottom: scenario 2060 RCP8.5, positive values= heat losses, negative values= heat gains

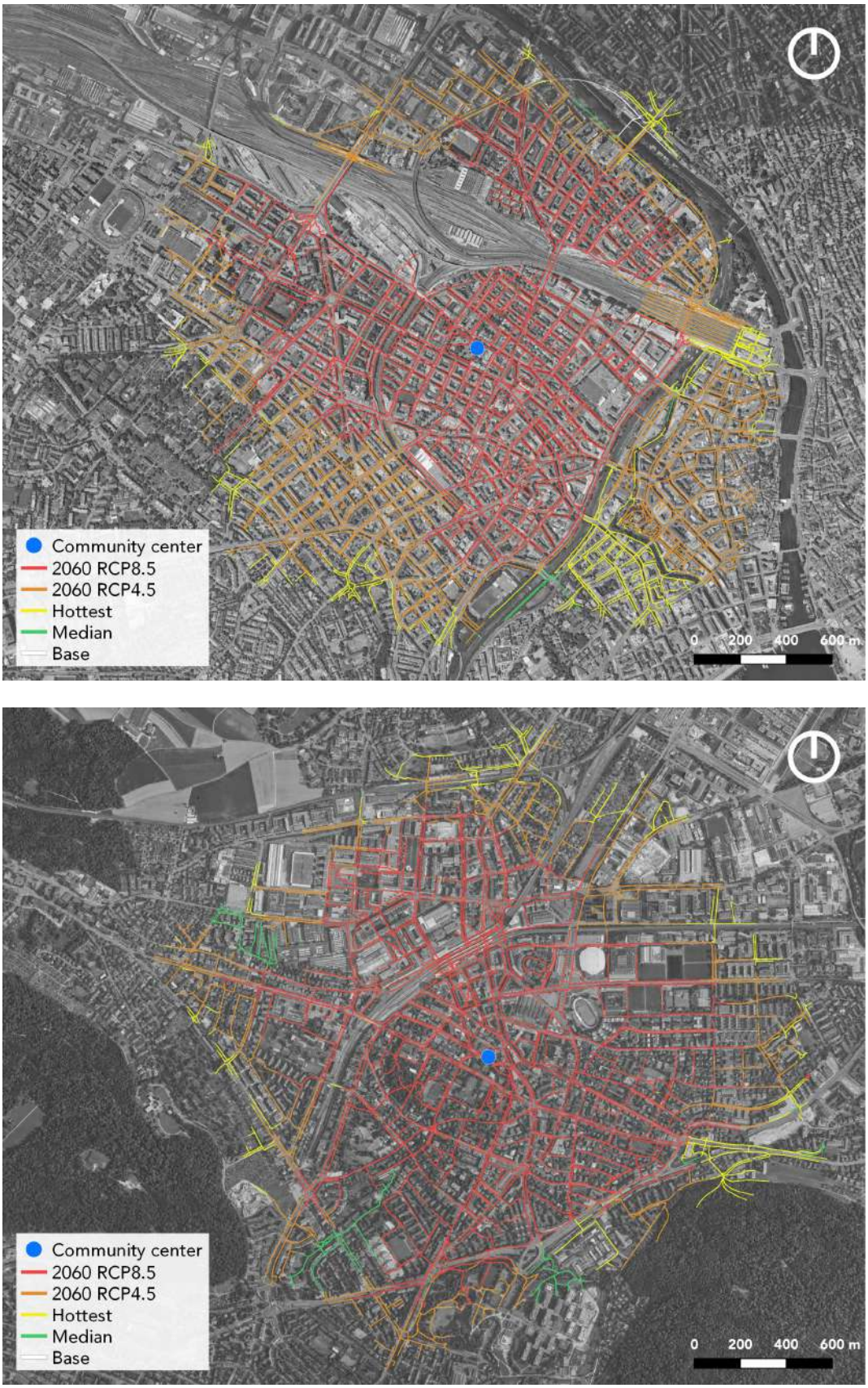

FIGURE 6: Comfortable reachable streets for different scenarios, top: CC Bäckeranlage, bottom: CC Oerlikon, basemap: (29)

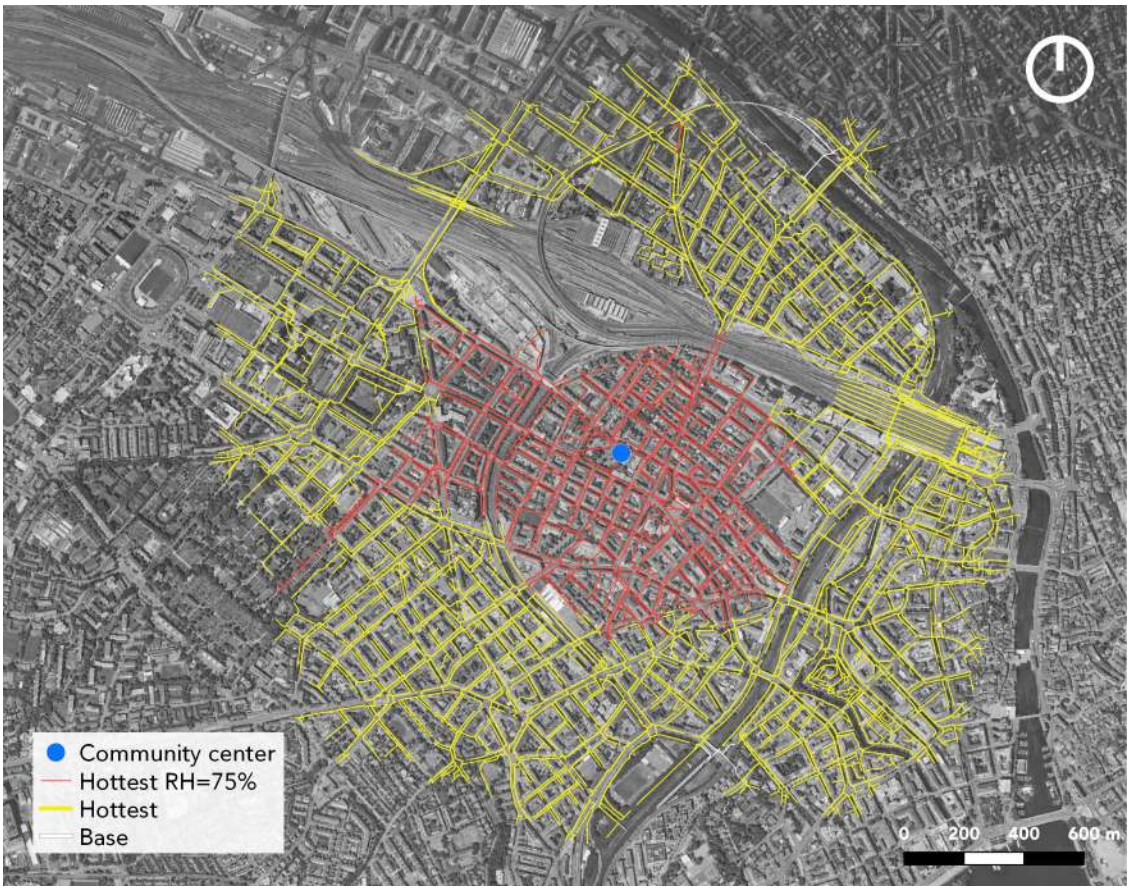

FIGURE 7: Comfortable reachable streets, sensitivity on relative humidity: CC Bäckeranlage, basemap: (29)

CONCLUSION

The research at hand applied a human thermoregulation model to comprehensive real-world data. On the one hand, we assessed OTC for the trips of a travel diary study and found that the pedestrian path choices in the current climate of Zurich do not suggest that pedestrians integrate anticipated heat stress in their path planning. There are indications that they do for longer trips, but the sample size is too small to draw robust conclusions. Nevertheless, the developed methodology can be used for other study cases where climate might significantly influence route choice. Most important, it was shown that this is possible with existing, mainly publicly available data. Extending this work by modeling the route choice using discrete choice models would provide additional valuable findings. These insights could be implemented in software to model pedestrians more accurately in hot temperatures. Furthermore, the results could be used to incorporate OTC in navigation software such as Google Maps.

Further, we developed a tool to assess OTC-corrected accessibility based on an OTC-corrected routing engine. We evaluated its usefulness for two case study locations in Zurich. It could be shown that the current climate does not affect accessibility thanks to relatively low RH. A sensitivity analysis showed that high relative humidity reduces OTC severely during hot temperatures. The results for the climate forecasted for 2060 showed remarkable reductions in OTC-corrected accessibility. In general, the developed tool can be employed in the analysis stage of projects that aim to secure the outdoor thermal comfort of urban dwellers by indicating the need for improvements spatially. A great advantage compared to the existing methods of OTC assessment (13) is the accessibility approach which permits quantifying the impact of interventions in terms of gain in comfortable walking areas or inhabitants for a given location. By modifying the parameters of the thermoregulation model, outdoor thermal comfort could also be assessed for particular groups of people and the public infrastructure related to them.

Despite the demonstrated contributions, some limitations have to be mentioned. The biggest one is that for the modeling, it is assumed that pedestrians walk precisely on the centerlines of the coded pedestrian network. In reality, pedestrians almost always have a margin where to walk on the sidewalk. This can drastically affect the pedestrian's OTC. The same issue also affects the behavior on public squares, where not all possible crossing possibilities are represented in the network. Furthermore, the threshold wt_{thr} used in this work depends on M. It is the mostly used in research, but its explanation is insufficient.

The presented work is not only of interest for practitioners and researchers in regions with harsher climates but due to the future increase of global temperatures, especially also for places where there is still time to react and implement adaptation measures to ensure attractiveness of the most fundamental transport mode: walking.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J. Hess; data collection: J. Hess; analysis and interpretation of results: J. Hess, K.W. Axhausen, V. Melnikov, A. Meister; draft manuscript preparation: J. Hess; manuscript review: K.W. Axhausen, A, Meister, V. Melnikov. All authors reviewed the results and approved the final version of the manuscript.

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