DEVELOPMENT AND APPLICATION OF 'THERMAL RADIATIVE POWER' FOR URBAN ENVIRONMENTAL EVALUATION

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ABSTRACT

We have developed a new evaluation method of "thermal radiative power" (TRP) for investigating the impact of building surface material albedo on urban environment. The simulation system ENVI-met is used. This system is a 3D computer model which analyzes micro-scale thermal interactions within urban environments. It simulates urban-scale environmental conditions such as roofs, exterior wall, and ground surface temperatures. Focuses of this research are on the climate change in urban and community scale in cold climates. The urban environmental analysis is carried out in a typical residential area in the central city of Montreal. The model for simulation is based on the existing urban conditions (building layout, building volume and ground surface properties). The TRP with varied building roof materials is calculated and compared. The effect of building surface materials on local climate is analyzed. The selected simulation area in this research is 300m by 300m. Each urban surface (ground, walls, and roofs) is analyzed individually, in order to determine the urban environmental contribution. The interaction between reflective surfaces is discussed. Representing the environmental conditions by TRP could help to define the impact of urban surfaces on the macro-climate (urban level) and micro-climate (community level).

KEYWORDS

Urban Climate; Thermal Radiative Power; Air Temperature; Mean Radiation Temperature; Relative Humidity

1 INTRODUCTION

The Urban heat island (UHI) effect is the phenomenon that a metropolis is usually significantly warmer than its rural surroundings. It occurs because city centre buildings and street surface materials, which have high heat capacities, store heat during the day, and release heat slowly at night. The adverse energy and environmental effects of UHIs, and methods to alleviate them, has become a major research topic in sustainability programs. Decreasing the energy consumption of buildings is an important topic in environmental engineering.
Daytime solar energy absorption is the primary cause of the urban heat island effect in summer. Pavements and roofs comprise over 60% of urban surfaces. Dark materials, dark pavements and roofs, absorb 80-90% of sunlight. Lighter materials, white roofs and lighter colored pavements, absorb only 30-65% of sunlight. There is an interaction of thermal radiation between roof, wall and ground surfaces. The use of reflective building surface materials is a critical solution for UHI mitigation [1, 4, 5, 6, 10, 21, 22, 23].
A large number of studies are currently attempting to demonstrate the extent of the UHI effect in cities. Some studies are using averaged Land Surface Temperature (LST) [15, 18, 20],

derived from satellite data. However, observed LST depends on spatial resolution, because of the different land cover types. In most present studies, a spatial resolution of 1 km^2 is used. This ignores land cover characteristics on a community scale.

Furthermore, LST derived from the satellite database ignores the contribution from the surface of exterior building walls. This is a serious deficiency for the consideration of urban solar heat absorption and reflection. This is especially relevant for mega cities that have a high density of high-rise buildings. This research will provide a new evaluation method for assessing the impact of building surface solar reflectance on the UHI effect. The TRP, released from the urban surfaces, is not used in existing studies, even though it is a suitable indicator to represent the impact of solar heat absorption.

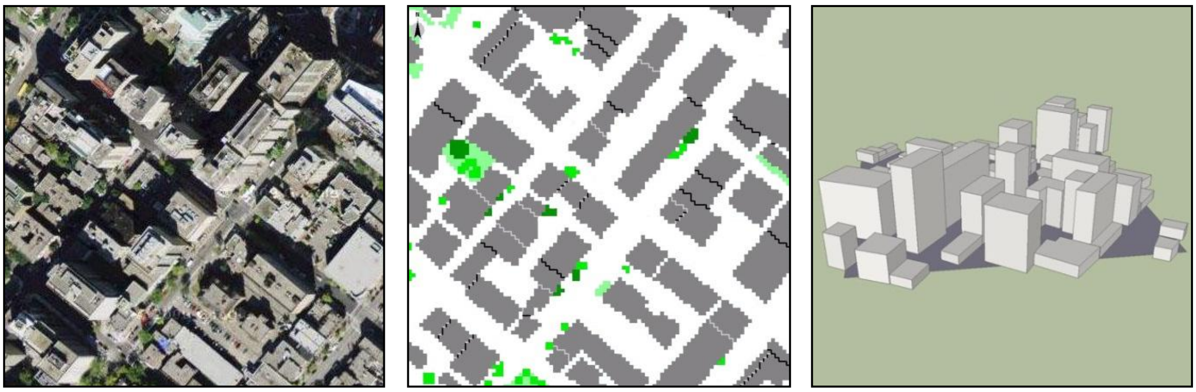
Many researchers have focused on the building surface materials, LST and urban heat island problem. Most studies have analyzed measured climatological data and demonstrated the correlations with urban development [3, 9, 15, 18, 20]. Very few have studied the UHI contribution from each environmental effector in micro scale, that directly affect the outdoor thermal comfort. In this research, the thermal radiation from urban surfaces (such as building roofs, exterior walls and ground surfaces) will be simulated, using a micro-scale urban simulation model. Both an urban and a community scale will be analyzed. The simulation will be helpful to determine the contributions of each component, and to determine the optimal combination of urban surface properties.

In addition, most present studies are focused on the UHI effect in hot and dry cities. The UHI effect in cold climates, such as Canada cities, should be further investigated. In this research, a new UHI evaluation system is proposed and applied in the city of Montreal. The objectives of our study are to: (1) define the new UHI evaluation method TRP, and (2) demonstrate the qualification of the TRP to express the extent of UHI. This research will be an investigation of the methodology for UHI study, which contributes to environmental urban planning standards providing, that can be used in urban developments and redevelopments.

2 METHODOLOGY

2.1 Selected Simulation Area

The selected area is a high-density residential area, next to the city's main commercial area and a university. There are many high-rise residential buildings of more than 15 floors. Most of the ground surface is asphalt road. The area was 300 meters by 300 meters.



Aerial satellite view | Area input file to the ENVI-met | 3D image

Figure 1. Images of the selected area: 1) aerial satellite view pictures, 2) input file images for ENVI-met simulations, based on the aerial satellite view pictures, and 3) 3D images of the buildings volumes.

2.2 Urban Environmental Simulation

We used ENVI-met simulation model (a three-dimensional computer model that analyzes micro-scale thermal interactions within urban environments) to simulate the environmental conditions in the selected area. ENVI-met is designed to simulate the surface-plant-air interactions in urban environments. It has a typical spatial resolution of 0.5m to 10m, and a temporal resolution of 10 seconds. A simulation is typically carried out for at least 6 hours, usually for 24-48 hours. The optimal time to start a simulation is at night or sunrise, so that the simulation can follow the atmospheric processes. ENVI-met requires an area input file which defines the 3-dimensional geometry of the target area. This includes buildings, vegetation, soils and receptors. A configuration file, which defines the initialization input, is also required [12, 14, 16].

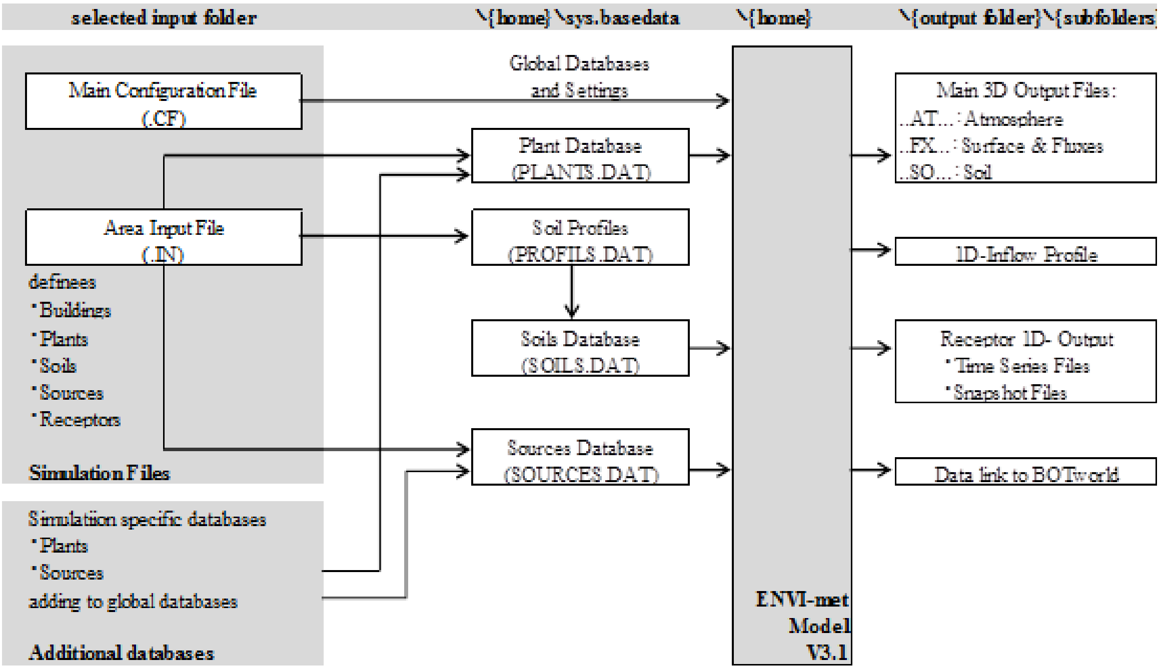


Figure 2. Data flow in ENVI-met V3.1 (http://www.envi-met.com/)

The data flow shown in figure 2 summaries the general interaction between input and output data. ENVI-met carries out detailed calculation in regards to [13]:

- shortwave and long-wave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation
- evapotranspiration and sensible heat flux from the vegetation into the air, including full simulation of all physical plant parameters (e.g. photosynthesis rate)
- surface and wall temperatures for each grid point
- water and heat exchange inside the soil system
- the calculation of biometeorological parameters, such as Mean Radiant Temperature (MRT) or Fanger's Predicted Mean Vote (PMV) value
- the dispersion of inert gases and particles, including sedimentation of particles at leaves and surfaces.

For these simulations, the geometry of urban street canyons in selected area is identified using satellite pictures and street maps from Google Map. Area input files were built by ENVI-met; we input satellite pictures into the editing files, and defined the ground, vegetation, building facade and building layout by cubic grids of 27m^3 (3m×3m×3m). The simulations were run for 24 hours, starting from one hour before sunrise (4am). We simulated this area in summer. The weather data was obtained from the "Weather Spark" database. However, with the spatial limitation of the simulation model, a deviation will emerge around the edge of simulation model. This deviation will also affect the UHI simulation results with ENVI-met.

2.3 Definition of 'Thermal Radiative Power'

The thermal radiative power (TRP) of a black surface, given by the Stefan–Boltzmann law is obtained by:

$$P = \sigma \bullet A \bullet T^4 \tag{1}$$

For surfaces which are not black bodies, one has to consider the (generally frequency dependent) emissivity ε . This emissivity has to be multiplied with the radiation spectrum formula before integration over the wavelength spectrum. If it is taken as a constant, the resulting formula for the power output can be written in a way that contains ε as a factor. The following equation is used for calculating the TRP in this research:

$$P = \varepsilon \bullet \sigma \bullet A \bullet T^4 \tag{2}$$

Where:

P: Thermal Radiative Power (W)

ε : Emissivity (Soil: 0.92-0.96; Concrete: 0.94; Asphalt: 0.9-0.98)

σ: Stefan-Boltzmann Constant = 5.67×10-8 ($W \bullet m^{-2} \bullet K^{-4}$)

A: Radiating Surface Area (m^2)

T: Absolute Temperature (K)

3 RESULTS

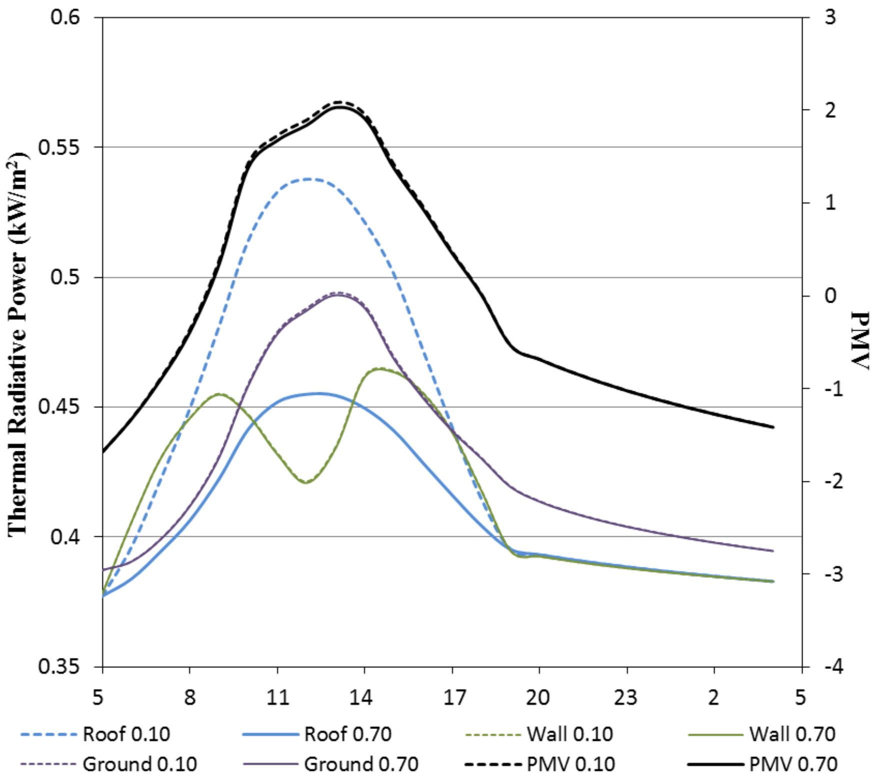


Figure 3. Averaged TRP of each urban surface elements (Roof, Wall, and Ground) per m^2, and averaged diurnal PMV at 1.8m above the ground on a typical Summer day (from 5am, 22 July, to 4am the next day) in the selected area, with two roof types (Type 1: albedo 0.10; Type 2: 0.70). Diurnal PMV with lower roof albedo is slightly higher than that with higher roof albedo.

The Averaged TRP per m^2, from each element of urban surfaces at daytime and night time is calculated and showed in figure 3. Type 1 represents the model with roof albedo of 0.10; type 2 represents the model with roof albedo of 0.70. With increasing the roof albedo, the TRP from roof is decreased 15.4% (0.08kW/m^2) at 1pm. Meanwhile, the TRP from walls and ground is also slightly decreased (0.2% from ground, and 0.1% from walls). This could be considered as the reason of the PMV difference. PMV that observed in type 2 is 0.05 lower than that in type 1 in the midday from 10am to 2pm. At midnight (1am), the TRP from

ground, building walls, and roofs in two types of model are almost the same. This could explain the same PMV that observed during the night time; the difference is lower than 0.01 after 6pm. This comparison demonstrated the interactions among each urban surface, because the TRP of ground and walls are reduced by increasing the albedo of the roofs.
Figure 4 compares T_a, T_{mrt}, and relative humidity with two model types. Diurnal T_a and T_{mrt} with lower roof albedo are slightly higher than that with higher roof albedo, and relative humidity is lower for the model with lower roof albedo. The effect of roof albedo on T_a, T_{mrt}, and relative humidity is pronounced during daytime (from 11am to 7pm). During this period, T_a difference is around 0.2^{O}C, T_{mrt} difference is around 0.06^{O}C, and relative humidity difference is over 0.8%. At nighttime (after 7pm), the temperature difference between two models is close to 0^{O}C. This is to say, the effect of roof albedo on community-scale thermal environment is mainly during daytime. Additionally, higher roof albedo could also reduce the surface temperature of buildings, leading to a higher indoor comfort, lower energy consumption, and lower heat emission. However, the impact of heat emission from indoor of buildings is not included in this simulation. Therefore, the environmental benefits of high albedo roof are even higher than the results shown by these simulations.

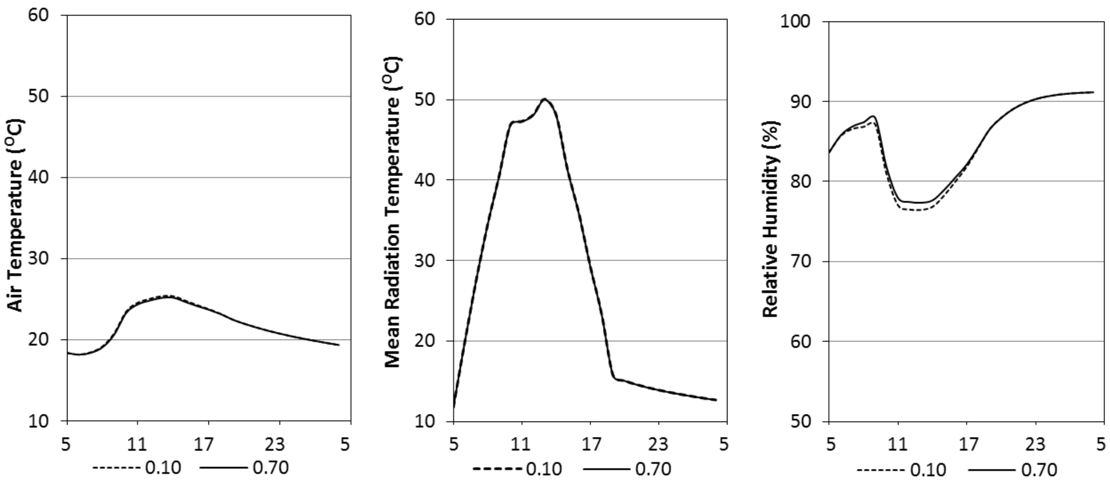


Figure 4. Averaged diurnal air temperature (T_a), mean radiation temperature (T_{mrt}), and relative humidity at 1.8m above the ground on a typical Summer day (from 5am, 22 July, to 4am the next day) in the selected area, with two roof types (Type 1: albedo 0.10; Type 2: 0.70).

Furthermore, the correlation between TRP change (TRP change = TRP of type 1 – TRP of type 2) and urban environmental condition changes (T_a change = T_a of type 1 – T_a of type 2; T_{mrt} change = T_{mrt} of type 1 – T_{mrt} of type 2; Relative humidity change = Relative humidity of type 1 – relative humidity of type 2; PMV change = PMV of type 1 – PMV of type 2) are indicated in figure 5. All coefficients of determination (R^2) are greater than 0.80. Inspecting the correlation between TRP change and T_{mrt} change, the impact from the TRP change of the ground (R^2=0.99) is much bigger than that from the walls (R^2=0.95) and roofs (R^2=0.83). On the other hand, comparing TRP change from roofs , walls and ground, the TRP change of the roofs is showing a higher impact on T_a (R^2=1), relative humidity (R^2=0.99) and PMV (R^2=0.99). The effect of TRP and T_{mrt} at ground level is highly correlated. The effect of each urban surface element (roofs, walls, and ground) on the urban thermal comfort is investigated separately. The result verified the TRP as an urban environmental evaluation index.
The interactions among the ground, building walls, and roofs are observed in this comparison. TRP from Ground contributes almost 100% to the radiative environment in community scale, because the released radiative power directly effects to the human height level. The effect of TRP from building walls on comfort is somewhat lower. This is because some part of the TRP from walls will be directly reflected to the sky, and some part of it will be locked in the

urban canyon. Inter-reflection also occurs between surrounding walls and ground. TRP from roofs slightly affects the urban radiative environment, because very small part of TRP will be reflected to the surrounding walls (this fraction becomes obvious with big differ of building height, such as central area of cities), and most part of it will be released to the sky.

The estimation of TRP can make a significant contribution to the process of urban environmental analysis for urban development or redevelopment, helping to develp policies and guidelines. TRP could also be carried out by field measurement for existing urban environmental evaluation, in order to develop specific promotion scenarios. In such case, measuring the surface temperature, calculating the emitted radiation intensity, and multiplying it by the area of each surface (walls, roofs, and ground), one can develop a TRP index for each community area.

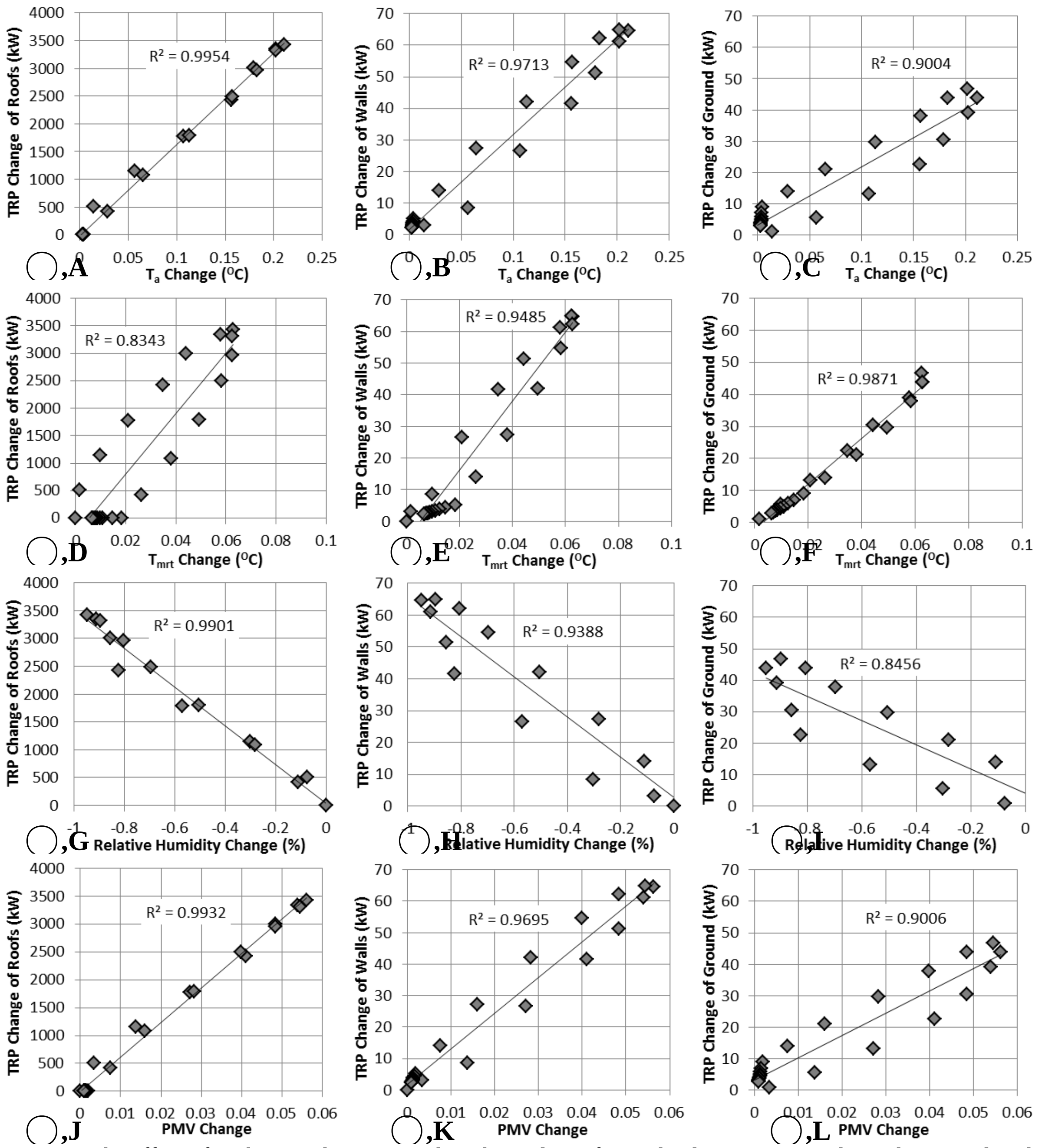


Figure 5. The effect of each TRP changes to urban thermal comfort. The data is at 1.8m above the ground in the selected areas 24 hours of a typical day in summer (from 5am, 22 July, to 4am the next day). R^2= coefficient of determination. TRP changes are proportional to T_a, T_{mrt} and PMV changes, inversely correlated to relative humidity change.

4 CONCLUSION

In this study, TRP is introduced as a new standard for evaluating urban environment. Compared to LST, TRP could indicate the thermal effect from each urban surface element in community scale, and evidence the impact from each surface element. Two types of urban model are simulated and compared. Changing the albedo of building roofs from 0.1 to 0.7, the TRP from roofs during the typical summer day is decreased obviously (around 6% to 15% during 7am to 5pm). The TRP from walls and ground are also somewhat decreased (around 0.02% to 0.20% during 7am to 5pm). The impact of TRP from each urban surface element on the urban thermal comfort are compared and discussed. Changing of TRP shows a strong correlation with changing of urban thermal comfort indicators, such as T_a, T_{mrt}, relative humidity, and PMV. It is investigated that, TRP is a qualified index for urban environmental evaluation in the three-dimensional urban respect.

Development and application of this index could help to specific the phenomenon of urban climate change, and helps to figure out the solution scenarios for urban climate change mitigation. In addition, application studies in various urban areas with various building types, vegetation plans, and urban surface materials should be carried out in the next stages.

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