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Thermal performance of a green roof based on CHAMPS model and experimental data during cold climatic weather

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ABSTRACT

Green roofs are increasingly implemented in cities around the world. They have the potential to improve thermal performance of building systems through evapotranspiration, thermal mass, insulation and shading. Several studies have analyzed the heat flow impact of green roofs in hot weather, but few studies have examined the thermal performance during cold conditions. Roof membranes are known to fail in cold climates due to stress caused by large temperature fluctuations. A green roof can reduce the daily membrane temperature fluctuations ($T_{max} - T_{min}$) by an average of 7°C. This study presents an experimental investigation of a large extensive green roof on the Onondaga County Convention Center in Syracuse, NY from November 2017 to March 2018. The model known as CHAMPS has been applied to simulate the temperature profile through the layers of the green roof. In early winter without snow, the temperatures of the growth medium and roof membrane follow the diurnal cycle of ambient air temperatures with smaller amplitude. An average seven hour peak delay is observed. Under extremely cold weather, snow acts as an insulator. The temperature of the growth medium on the Convention Center remains slightly above freezing and is relatively steady when there is significant snow, even during extremely cold temperatures. Heat flux is dominated by the temperature gradient between interior space and the snow layer. On the basis of this work, it is shown that the CHAMPS model can play a valuable role in informing green roof design decisions.

KEYWORDS

Green roof; temperature fluctuation; snow; CHAMPS; roof membrane

INTRODUCTION

Green roofs normally consist of multiple layers, for example, vegetation, growth medium, drainage, waterproof membrane, and roof surface. They can vary from one design to another based on regional climates. While green roofs have been implemented in cities for years, the interest in installing green roofs in both retrofit and new construction is still increasing. Thermal benefits of green roofs include saving energy for space heating and cooling, and mitigating urban heat island effects due to evapotranspiration, direct foliage shading, the insulation effect of the soil and other factors. Another benefit is that the green roof can block solar radiation, thus protecting the base roof membrane from temperature fluctuations. In winter, a green roof can shield the roof membrane from extreme cold and from sudden changes in ambient air temperatures. Daily temperature fluctuations create thermal stress in the roof membrane and reduce its longevity (Teemusk and Mander, 2010).

The need for tools that designers and architects can use to assess the potential thermal benefits of green roofs is growing. Some studies investigate numerical models in DesignBuilder, PHPENICS, and EnergyPlus for green roof energy consumption simulations (Ran and Tang, 2017; Zhang et al. 2017; Lazzarin et al. 2005). In this paper, we present a new platform to inform the design process, the CHAMPS-BES model (Combined heat, air, moisture and pollutant simulations in building envelope systems). This model is used to assess the long-term energy and durability performance of building envelop systems.

Snow cover may provide a natural insulation layer in winter, which affects the cold weather performance of green roofs. There are two objectives of this study, both related to minimizing temperature variations that can damage the waterproof membrane on a roof. The first objective is to determine the impact of adding a green roof as a retrofit to a traditional roof on a large building in a cold climate. The second objective is to determine the impact of a significant snowpack on the retrofitted green roof.

METHODS

Study Site

This project focuses on the green roof on the Onondaga County Convention Center in Syracuse, NY. Syracuse is located at the northeast corner of the Finger Lakes region. It is known for its snowfall, in part due to the lake effect from nearby Lake Ontario. Based on the data from the weather station at Hancock International Airport (National Weather Service, 1938-2016), there are on average 65.2 days with snow per year. Total yearly snowfall depth is increasing (Fig.1). Snow mainly falls between the months of November and March. January is the coldest month and also has the most snowfall (Fig. 2).

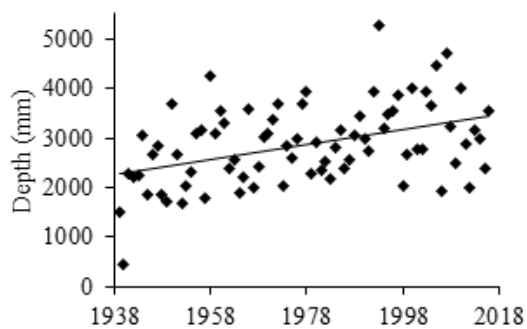


Figure 1. Yearly snowfall depth (1938-2016)

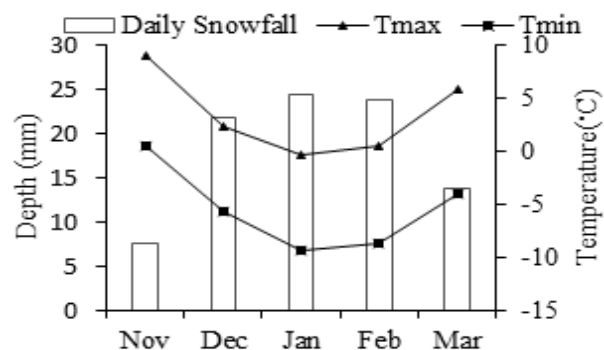


Figure 2. Daily snowfall and daily minimum and maximum air temperature (1938-2016)

The Convention Center green roof was retrofitted in 2011. The roof consists of the following layers: a steel deck, a gypsum board, extruded polystyrene insulation, a second gypsum board, a drainage mat, a waterproof membrane and a coarse growth medium layer (Fig. 3). The insulation layer and layers below are original to the building. Table 1 summarizes the main thermal properties of the layers of the green roof. The total area of the green roof is 5600 m². Plant species on the roof include *Sedum album*, *Sedum sexangulare*, *Sedum rupestre*, *Sedum floriferum*, and *Phedimus taksimense* (Squier and Davidson, 2016).

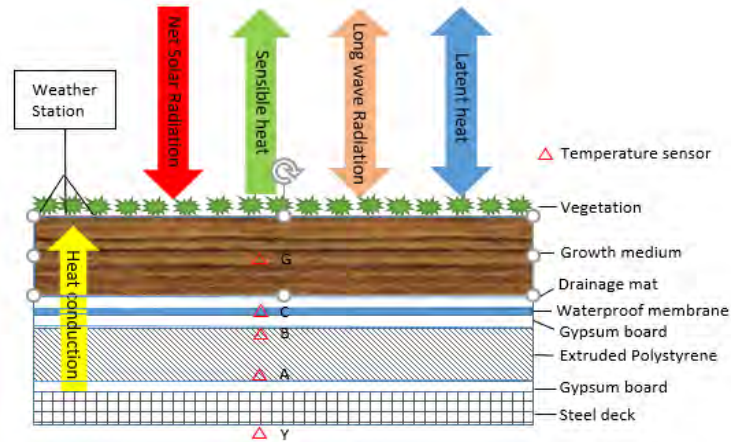


Figure 3. Schematic drawing of the Conventional Center green roof

Table 1. Thermal properties of the Conventional Center green roof

Layers	Thickness (cm)	Density (kg m ⁻³)	Thermal conductivity (W m ⁻¹ K ⁻¹)	Specific heat capacity (J kg ⁻¹ K ⁻¹)
Growth medium	7.62	790	0.36	1000
Drainage mat	0.63	1000	0.92	1000
Waterproof membrane	0.12	1400	0.43	1000
Gypsum board 2	1.59	700	0.16	870
Extruded polystyrene insulation	7.62	100	0.03	1300
Gypsum board 1	1.27	700	0.16	870
Steel deck	7.62	3600	20	700

Instrumentation and measurement

The thermal monitoring system of the green roof has been equipped with CR1000 Dataloggers and AM 16/32B Multiplexers (Campbell Scientific). A weather station on the roof includes air temperature, relative humidity, wind direction and windspeed. T109 temperature sensors (Campbell Scientific) are positioned at five different heights within the green roof (Fig. 3). This temperature profile is measured at five locations on the roof; only one location (station1) is used in this study. Temperature data are averaged and reported at hourly intervals. Interior temperatures are controlled by an HVAC system. Temperature sensor Y is mounted on the ceiling of the Exhibit Hall of the Convention Center to measure the indoor temperature. Solar radiation data are obtained from Syracuse University Weather Station, which is 1.9 kilometers from the green roof. The measuring period used for thermal analysis of the green roof is November 2017 to March 2018. Manual snow depth measurements have also been conducted.

CHAMPS simulation

Several input parameters are needed in the CHAMPS model. The weather data discussed above are used as inputs. Properties for the layers of the green roof are taken from manufacturer specifications. Snow cover is not considered in the simulation. The exchange coefficient of heat transfer is taken as 15 W/m²K, due to the large surface area of sedum plants. To assure the validity of the simulation results of CHAMPS, the model is validated using parameters for the green roof with experimental data from early November (11/1/2017-11/7/2017). After the validation, two case studies are performed based on the objectives:

- To determine the impact of the retrofit, CHAMPS is run for the case of the Convention Center traditional roof before the retrofit. The output of CHAMPS is compared with the experimental data from the green roof.
- To determine the impact of a snowpack on the green roof, CHAMPS is run for the green roof without snow. The output of CHAMPS is compared with experimental data from the green roof with a significant snowpack.

RESULT

Winter thermal performance

During the experimental campaign period, there were 87 days with snowfall in Syracuse. The average ambient temperature on the roof was -0.24°C . Temperature profiles for nine days in early November and early January are shown in Fig. 4. The extruded polystyrene layer contributes most to the effective insulation across the roof layers, where the largest temperature difference is between sensor A and sensor B. Early November represents typical early winter without snow in Syracuse. The temperatures of layers above the extruded polystyrene insulation (B, C, and G) follow the diurnal pattern of ambient air but with slightly smaller diurnal variation. An average of 7 hours delay in peak temperature is observed based on the temperature in the growth medium (G), compared to the ambient temperature. Early January represents a typical snowy winter period in Syracuse with a significant snowpack over the full nine-day period. Snow depth along the roof from west to east measured on January 9, 2018 is highly variable (Fig. 5). The snow depth on top of station 1 was 0.1 m. Figure 4 shows that the temperature of the growth medium was roughly constant at around 0°C . This is true even when the ambient air temperature was -20°C on occasion. This shows that the impact of snow accumulation on roof temperature is significant. A similar finding was reported by Getter et al (2011).

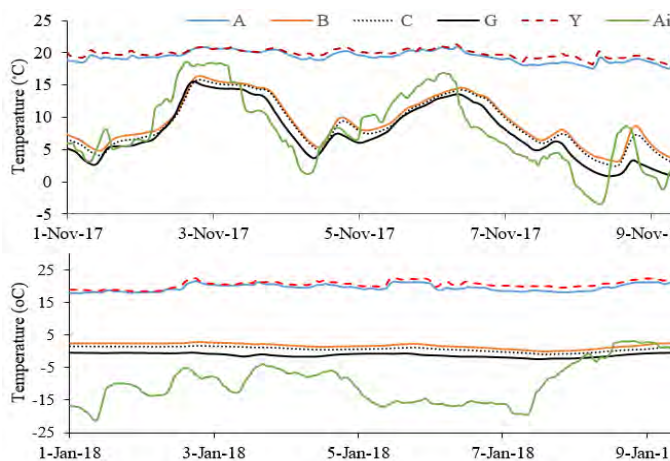


Figure 4. Temperature profiles in early November (no snow) and January (snow cover)

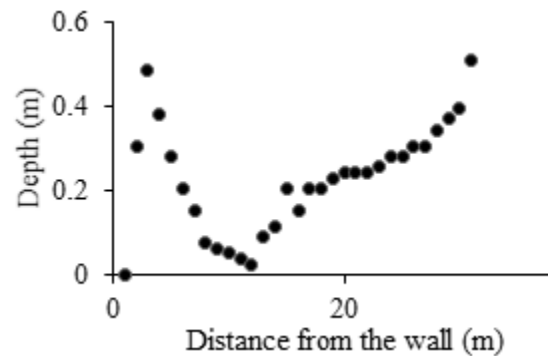


Figure 5. Snow depth measurement on Jan-9-2018

Model validation

The developed green roof model in CHAMPS has been validated using the data of the first week in November. The simulated growth medium temperature is compared with the measured data (temperature sensor G) in Fig. 6. On average, the CHAMPS model overpredicts the measured

temperature by only 17%. The simulated green roof model appears to be reliable and can be used to simulate the traditional roof and green roof without snow cover.

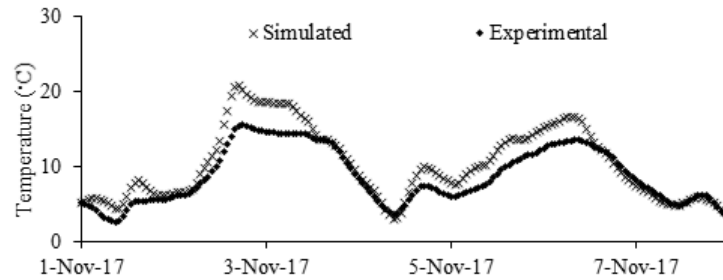


Figure 6. The validation of the CHAMPS model using experimental data for layer G

Temperature fluctuations on the membrane

The daily fluctuation is defined as the difference between daily maximum temperature and daily minimum temperature. A traditional roof model was developed in CHAMPS by deleting the growth medium and drainage mat layers. The temperature fluctuations of membrane on the traditional roof are far greater than those measured on the green roof in early winter (Fig. 7). The growth medium and drainage mat clearly play an important role in reducing temperature fluctuations on the membrane.

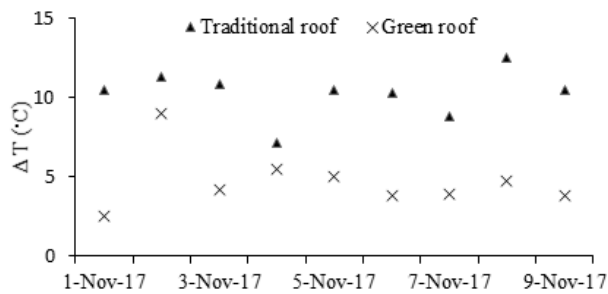


Figure 7. Temperature fluctuations at the membrane of the simulated traditional roof and measured on the green roof

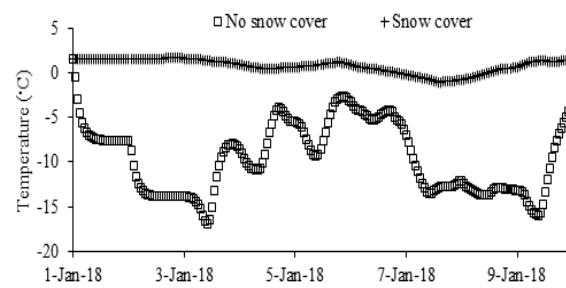


Figure 8. Temperature of the membrane for two conditions: simulated result with no snow cover and measurements with snow cover

Insulation effect of the snow cover

The green roof is simulated without a snow cover using early January meteorological data in CHAMPS. The membrane temperatures without a snow cover are compared with the measured membrane temperatures under snow (Fig. 8). The role of snow accumulation in reducing temperature fluctuations is significant. Without snow cover, under the same weather conditions, the membrane temperature could range from -18 °C to 0°C. Under the accumulation of snow, the protection provided by the growth medium becomes negligible compared with the protection provided by the snow. The benefit of having a green roof is decreased in cold weather. This result has been reported in other studies (Lundholm et al. 2014).

DISCUSSIONS

Green roofs modify membrane temperature fluctuations in the winter. During times without snow cover, those membranes absorb solar radiation and are subjected to moderate temperatures. At night, exposed membranes re-radiate the heat and their temperatures drop (Liu & Baskaran, 2003).

Extreme temperature fluctuations are a major cause of membrane failure. Vegetation and growth media of green roofs improve the insulation properties of buildings and decrease the absorption of solar radiation, protecting the membranes. During snowy winter periods, snow cover promotes higher survival of perennial plants due to warmer soil temperatures. The snow cover also decreases temperature fluctuation at the membrane. In this study, a simulation using CHAMPS has been based on an energy balance through layers. Wind effects and moisture properties have not been considered due to lack of data, although those are crucial factors in assessing the overall energy performance of green roofs. Next, moisture and wind effects will be added to the simulation.

CONCLUSIONS

In this study, a large extensive green roof in Syracuse, NY was monitored during the winter months to understand its thermal performance. Furthermore, a green roof model was developed and verified by CHAMPS software. During early winter months, the plants and growth medium add thermal mass to decrease the membrane temperature fluctuations. In very cold weather, snow accumulation acts as effective natural insulation, isolating the roof from the ambient environment. CHAMPS software enables the user to add a green roof to any roof design. It is a systems model accounting for heat, air, and moisture. CHAMPS is a useful tool to the quantitative evaluation of the energy benefits of green roofs under regional climates, and can be of value to designers when considering retrofit additions of green roofs on buildings.

ACKNOWLEDGMENT

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