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Green roof thermal buffering: Insights derived from fixed and portable monitoring equipment

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ABSTRACT

Thermal buffering of the 27,316 m^2 Jacob K. Javits Convention Center Green Roof (JJCC Green Roof) was investigated in the field, as well as in the laboratory in order to determine its ability to insulate a building. An instrumented replica of the green roof cross section was developed to elucidate the inner-workings of the system. During the course of a year a total of twelve field monitoring campaigns were conducted to measure temperatures with 249 images collected at sixteen different locations (eight exterior and eight interior). During this first sequence of measurements, the north green roof had already been completed, while the south green roof was gradually being installed. Additional field imaging was performed on two separate days in August (on 08/08/15, 08/22/15), and on one day in January (on 01/22/16) between sunrise and sunset (generating an additional 850 images). To isolate the thermal performance of individual components of the roof structure, a physical model of the roof was constructed in a laboratory, instrumented with thermistors, and subjected to a heat lamp. A one-dimensional heat conduction model was used to investigate physical relationships revealed by the field and laboratory observations, and represents the experimental data well. The results indicate that the construction of the green roof significantly reduces heat flux through the convention center roof. The mean internal and external temperatures on the north and south sections of the roof on the first monitoring day (when the north green roof was complete, but the south green roof had not yet been installed) and the last monitoring day (when both north and south green roof sections were complete) are provided to support the insulating value of the green roof layers. The mean exterior temperature on the south roof on the first day of monitoring was 53.9 °C and 37 °C on the north roof. The mean exterior temperature on the south roof on the last day of monitoring was 24 °C and the north roof 28 °C.

1. Introduction

Research concerning the thermal performance of green roofs in urban and suburban settings is relatively new with most research conducted and published outside of the United States [1]. The majority of this work underscores the thermal benefits of green roofs over traditional black tar asphalt and gravel roofs [1–3]. Green roofs provide physical protection of the conventional roof from solar radiation and reduce both daily and seasonal variations in surface temperature [4,5]. This buffering is accomplished through reflection, convection, vaporization, and eventual transmission processes. Green roofs typically have a higher albedo than traditional black roofs, and thus are able to reflect a larger fraction of the incident solar radiation away from the roof surface. Radiation that is not reflected away from the surface heats up the green roof elements (its vegetation, growing media, and the moisture stored within it). Of the absorbed energy, the fraction that is utilized for evaporation, e.g. the vaporization of liquid moisture stored in the green roof, does not contribute to an increase in the actual surface temperature of the green roof, nor is it transmitted downward to the actual structural roof below it. The processes of reflection, absorption and vaporization all contribute to a reduction in the amount of energy transmitted downward to the structural roof surface, e.g. thermal buffering, and may also have value in reducing the roof's individual contribution to the local urban heat island (UHI) effect [1,6–8,21], a topic we explore in greater detail in a companion paper ([9] in preparation)).

Recent empirical research and modeling, while minimal, provides evidence of these claims. For example, the summertime surface temperature of a 72 m^2 model green roof with low slope and

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Table 1
Javits Green roof materials, not including the structural roof.

Material Description	Product Code
Pre-cultivated vegetated mat	XF301
Growing medium (1.5–5 cm)	XeroTerr
Water retention mat/fleece	XF157
Drainage mat (2 mm)	XF1084
Root barrier	XF112

a high roof-to-wall ratio in Ottawa, Canada, was rarely above 30 °C, while the temperature of an adjacent conventional roof with waterproof membrane was regularly over 70 °C in the same monitoring period. This green roof also experienced temperature fluctuations of less than 6 °C, compared to fluctuations of up to 45 °C in the reference roof, lowering its average daily energy demand for air conditioning by 75% (from 6.0–7.5 kWh/day to 1.5 kWh/day) [10]. Moseley et al. [11] reported that a green roof in Chicago was 22 °C cooler during hot weather than the membrane temperature. Compared to a white roof, this green roof had 6–10% lower heating costs and 7–15% lower cooling costs, translating to a 6–10% reduction in total modeled annual energy use, and a reduction of 6–10% in annual energy expenditures.

This study investigates the thermal performance of the 27,316 m^2 Jacob K. Javits Convention Center Green Roof (JGR). The goal was to quantify heat flux through the JGR, as well as through the membrane roof that is under it. The observations began prior to installation of the green roof, and included an extensive experimental campaign, including field and laboratory measurements and mathematical modeling. No other efforts to quantify changes in thermal conditions of a green roof as it was built could be found in the literature, nor do any other researchers attempt to identify which strata of the roof provides the greatest thermal buffering. For the first time, the temperature of a large green roof was compared to that of an adjacent black top roof.

2. Methods

2.1. Site description

The JGR was completed in the spring of 2014 and consists of two roof sections (Fig. 1). At the beginning of this study, the north section of the green roof had already been installed. By contrast, the monitoring campaign on the south roof spanned a period of time beginning with the removal of the old roof layers, and continuing through the end of green roof construction. The JGR is an extensive green roof system (XeroFlor XF301 + XT), shown in section in Fig. 2, with the product codes for key components provided in Table 1. Throughout the monitoring campaign, the convention center was heated or cooled in response to local climatic conditions. Typically, the convention center was cooled (through air conditioning) at least one day before and throughout the duration of a convention event; the heat was never turned off for more than a half a day in the winter.

2.2. Field monitoring campaign

The full field monitoring effort included both fixed and mobile sensors used to assess the JGR's ability to manage stormwater and provide thermal buffering. Only those sensors used in the thermal buffering study are described here. These included four weather stations, a portable infrared camera, and a portable thermometer. Table 2 includes specifications for all sensors employed in the field investigation.

The weather stations log temperature, precipitation, wind speed and direction, four component radiation at five-minute intervals onto a Campbell Scientific CR1000 logger, connected to a cellular modem for real time transmission of the data to the research team. One of the weather stations (Station 1) was installed on a building to the north of the JGR, while the second (Station 2) is positioned on a street pole to its east. Two additional stations (Station 3 and 4) are installed on the north, and south, sections of the roof, respectively. The rain gauges were calibrated bi-yearly according the procedures in the Campbell Scientific TE525WS Rain Gauge manual. All other weather station sensors were calibrated based on the manufacturer's recommendations.

An infrared camera, FLIR Model T440 with a 45 mm, 90° wide lens, was used to measure roof, ceiling, and floor surface temperatures at 76,800 pixels and with multi-spectral dynamic imaging. The infrared camera was initially factory calibrated, but a reference black body of known temperature was also used for in-situ calibration. The process adjusting the camera's emissivity settings until its reading matched the known infrared emissions associated with the black body at that temperature.

The portable infrared camera was used to image the exterior and interior of the roof at the monitoring locations indicated on Fig. 1. Imaging days were selected to avoid events at the Convention Center. Fifteen imaging days were conducted between 2013 and 2016. During the first season [2013–2014], the north green roof had already been completed but the south green roof was gradually being installed. A total of 249 images were collected on twelve

Table 2
Weather station equipment description and specifications with data collection requirements.

Equipment	Parameter Measured	Specifications	Time Active	Recording Interval
Young Wind Sentry Anemometer – Model 3002	Wind speed, direction	Speed: ±0.5 m.s, Direction: ± 5°	Aug 2013–Present	Average5 min
Texas Electronics Inc. Series Rainfall Sensor – Model 525	Total Rainfall	1.0% @ 10 mm/h or less	Aug 2013 – Present	Average 5 min
Hukesflux 4 component net radiation sensor – Model NR01	Incoming Solar/Shortwave, Incoming Longwave, Outgoing Solar/Shortwave, Outgoing Longwave	±10%	Aug 2013 –– Present	Average 5 min
Campbell Scientific Temperature and Relative Humidity Sensor – Model CS215	Air temperature (shielded), Relative Humidity	±0.3C, ±4%	Aug 2013 – Present	Average 5 min
FLIR Thermal Imaging Camera T440	Roof, ceiling, floor temperatures	± 0.4C	Aug 2013 – Present	Frame Rate 60 Hz
FLIR TG54 Spot Infrared Thermometer	Laboratory green roof and structural roof temperatures	±0.1C	Aug 2013 – Present	2 s