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Energy savings potentials of commercial buildings by urban heat island reduction strategies in Montreal (Canada)

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ABSTRACT

The energy consumption of commercial buildings in Montreal (Canada) with absorptive and reflective skin materials is investigated. Four building prototypes (small office, medium office, large office, and retail store) with two types of heating systems (gas heating and heat pump) categorized based on vintage and HVAC system (old building with old HVAC, old building with new HVAC, and new building with new HVAC) are studied (total of 24 cases). For each case three simulations are performed using DOE-2 building energy model: (1) dark roof and walls with measured weather data: representing the actual case and the basis for comparing the effect on albedo enhancement, (2) cool roof and walls with measured weather data: determining the direct effect of increasing albedo of an individual building, and (3) cool roof and walls with modified weather data: predicting the effect of albedo enhancement in urban scale that contributes to weather condition. In all cases the effect of snow on the roof is considered and for modification of the weather data output of mesoscale meteorological simulation is used. Calculated energy consumption and energy expenditure showed that, in general, increasing the reflectivity of building skin saves energy and money. The surface modification is more beneficial for old vintage buildings. The maximum expenditure savings is about 11% for buildings with dark roof and walls, where the contribution of urban-scale increase in the surface albedo can be as high as 4% in the total energy expenditure savings.

1. Introduction

Absorption of solar energy in urban areas contributes to their higher air temperature compared to rural surroundings, known as Urban Heat Island (UHI). A well-documented effect of UHI is a decrease in summer thermal comfort or an increase in cooling energy demand in air conditioned buildings [1]. UHI has a small effect on the air temperature and heating energy demand in winter, particularly in cold climates, because: (1) the urban surfaces are covered with snow for a long period of the year, (2) the zenith angle that reduces solar energy on the ground is large, (3) the sky is mostly cloudy, (4) days are shorter, and (5) most heating happens in early morning, when there is not much sun. The beneficial effect of using reflective coatings for roofs and pavements on energy consumption of buildings is discussed in several reports (e.g., [2,3,34]). Meanwhile, new reflective materials are introduced to the market to decrease the small potential penalties of using reflective roofs [4–7]. Taha et al. [8] were pioneered in coupling a Planetary Boundary Layer (PBL) model to a Building Energy Model (BEM). URBMET (the PBL model; [31]) considers heat and moisture fluxes of the urban surfaces and DOE-2 (a BEM; [9]) calculates the energy consumption of buildings. The coupling of these models was offline and, after updating the weather data by PBL model output, BEM calculated the energy saving of increasing the albedo. Additionally, albedo control is shown to be an effective strategy to mitigate global warming [10,11].

Taha [12] showed that air temperature decreased up to 4 °C by increasing the albedo in Los Angeles basin; anthropogenic heat emission has a small effect on UHI in most parts of the US except for cold regions in winter. Akbari et al. [13] studied the effect of increasing albedo on the energy saving in buildings, using the Colorado State University Mesoscale Model (CSUMM) coupled with the Urban Airshed photochemical Model (UAM) to update the weather data and estimated the energy consumption change of buildings with DOE-2. They increased the albedo of roof and pavements, and the vegetation fraction of Los Angeles. Results showed a decrease of 20 ppb in peak ozone concentration and 20% reduction in cooling energy consumption.

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One of the widely used BEMs is based on the research performed by Salamanca et al. [14]. The BEM gets air temperature, humidity, and the amount of solar radiation from a mesoscale model. Outputs of BEM to the mesoscale model are temperature of urban surfaces and heat flux from buildings to the canopy. In this model, temporal variation of indoor air temperature is solved based on the sensible heat load difference between indoor and outdoor. Indoor air humidity is also solved following the same approach, based on the difference between indoor and outdoor latent heat load. Indoor sensible heat load is calculated by the convective heat transfer between room surfaces, air exchange of ventilation, anthropogenic heat of occupants, and other internal loads. Windows are assumed to be non-absorbent and temperature is constant along its thickness. Roos [15] and Karlsson and Roos's [32] approach is used to find the transmission of radiation through windows. The BEM can consider the comfort temperature (with its range) and maximum heating and cooling capacity of the HVAC system. The model was validated against other BEMs and good agreement was found. The coupled BEM-BEP model (building energy model coupled to building environment parameterization; [16]) was also validated using the experimental data of the BUBBLE project of Basel, Switzerland [17]. Offline simulation with the coupled model was performed in one dimension for the neighborhood of measurement-tower. The BEP resulted in smaller errors in estimating meteorological parameters compare to single layer and slab models for Montreal [21]. However, it was shown that the BEM cannot predict the building energy consumption accurately [18].

The coupled BEM-BEP is a simple model that does not consider the dynamics of the building and HVAC systems. Therefore, a BEM with a higher degree of complexity (namely DOE-2) with updated air temperature, humidity, wind speed, solar radiation, and cloud cover is used to calculate the annual energy consumption of buildings. Although the BEM coupled to WRF is simple in terms of calculating the energy consumption of buildings, it determines the heat emission from buildings to the canopy well [33,19]. The output of meteorological simulations in [20] is used to modify the weather file of the detailed BEM.

2. Methodology

Building energy calculations deal with sophisticated dynamics of HVAC systems, which cannot be modeled by a simple BEM designed for the scale of blocks of buildings (a few hundred meters). Even adding to the sophistication (e.g., dynamics of HVAC systems) of the BEM may not increase the accuracy of calculations because of the variability in type of systems in a grid cell of mesoscale meteorological models. Hence, a comprehensive BEM that has been widely used by the scientific community and has been tested with a variety of experimental data is employed for quantification of direct (less heat absorption by the building) and indirect (change in the ambient condition; air temperature, relative humidity, etc.) effects of increasing albedo on energy consumption of buildings. In this section the structure and calculation algorithm of the detailed BEM (DOE-2) is explained. Then, the prototype buildings (small office, medium office, large office, and retail store) are described. Afterwards, snow properties are discussed and the measured snow depths during 2005 are presented. Lastly, an algorithm to modify the weather file is discussed.

2.1. Simulation tool

DOE-2.1.E [9] is used to simulate four prototype buildings (small office, medium office, large office, and retail store). DOE-2 is well known for its capability of considering complicated dynamics of HVAC systems, and it is widely used by building professionals and the scientific community in order to analyze energy efficiency of given designs or efficiency of new technologies. DOE-2 consists of four simulation subprograms—namely LOADS, SYSTEMS, PLANT, and ECONOMICS. The LOADS simulator calculates peak zone loads of a building. The SYSTEMS simulator manages the operation of all HVAC components (including fans, coils, economizers, humidifiers, etc.). The PLANT simulator determines the operation of chillers, boilers, electrical equipment generators, and so on. The ECONOMICS simulator calculates energy and life-cycle costs. Sullivan and Winkelmann [22] evaluated the consistency of DOE-2 calculations with real case measurements in seven prototypical buildings. Their results showed a difference from 1% to 12%, varying by the building type.

2.1.1. Roof modeling in DOE-2

In DOE-2, a roof can be modeled as either a delayed or a quick structure. In delayed modeling the roof is modeled by defining the roof structure layer, simply using DOE-2 library materials or thermal properties of each layer. In this method all the thermal properties of layer, including their heat capacitance, are taken into account in the heat transfer calculations. The less accurate way of roof modeling is just to define the overall U-value of the roof, neglecting thermal capacity of the roof layers. The latter approach is applied to modeling the building roof with DOE-2 because DOE-2 limitations to change the roof characteristics during a simulation period (i.e., simulating the roof with and without snow layer). The heat equation through the "Quick Roof" can be written in the following form (Eq. (1)). For more details on modeling the snow on the roof (see [23]).

$$H = U_{\text{film}} \times A_{\text{roof}} \times (T_s - T_{\text{zone}}) \quad (1)$$

where H is the sensible heat, U_{film} is the combined conductance of the roof, inside film (and snow when there is snow on the roof), A_{roof} is the roof surface area, T_s is the outside roof surface temperature (snow surface temperature when there is snow on the roof), and T_{zone} is the zone space temperature.

2.2. Description of the buildings

Four prototype commercial buildings with flat roofs (small office, medium office, large office, and retail store) are studied. Each of the office building prototypes consists of six zones for each floor (four perimeters, one central, and a plenum zone) except for the old small office in which the plenum zone is eliminated. The retail building has five zones (core, front, back space, point of sale, and entry) and no plenum. Each prototype is simulated once with gas heating and electric cooling (using variable air volume, VAV, for large offices and packaged single zone for others) and once with all-electric HVAC systems (using packaged terminal air conditioner with heat pump for heating). Three vintages were considered for each building: old construction with old HVAC systems (pre-1980), old construction with new HVAC systems, and new construction with new HVAC systems. The vintages are different in thermal insulation, operation schedule, windows thermal conductance and shading coefficient, infiltration rate (leakage) through the building envelope, type and efficiency of HVAC system, and lighting intensity. The details of the building envelope characteristics and HVAC-systems specifications can be found in [24], and are summarized in Tables 1 and 2.

2.2.1. Small office building

The small single story has an area of 511 m^2 with 8 evenly distributed windows on left and right walls (4 windows on each side), and 12 windows on back and front walls (6 windows on each side), and a glass door on the front wall. Each window has a dimension of 1.5 m × 1.8 m (height × width). The window fraction is 24.4% for