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Effect of reflective pavements on building energy use

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ABSTRACT

Optimization of building energy use in an urban area requires understanding of the complex interaction between urban morphology, materials, and climate, which can have unanticipated effects on urban microclimates and building energy use. Reflective pavements reduce urban air temperatures and have been proposed as a mitigation measure for urban heat islands. However, the increased solar reflectivity also transports more solar radiation into (through windows) and onto adjacent buildings possibly increasing building energy use. The effect of albedo changes in the urban canopy floor surface on building thermal loads is investigated using the Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES). A case study for a four storey office building with 1820 m^2 floor area and 47% window to wall ratio in Phoenix, Arizona was conducted. Increasing pavement solar reflectivity from 0.1 to 0.5 increased annual cooling loads up to 11% (33.1 kWh m^{-2}). The impacts on annual heating loads and canopy air temperatures were small. The confounding impacts of canopy aspect ratio, building insulation conditions reflective of building age, and window type and size were also quantified. Policymakers should carefully weigh the benefits and local energy use implications of reflective pavements for each site to ensure their optimal application.

1. Introduction

The microclimate generated by the urban surfaces on and around a building affects human comfort and building energy use. Material properties, anthropogenic heat, geometry, and urban landscape features alter surface temperatures and energy fluxes between the ground and the atmosphere. For

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instance buildings close to parks or especially areas with abundant reflective roofs (Mackey et al., 2012) are exposed to cooler air than buildings in areas with predominantly (low albedo) asphalt surfaces. Reflective building roofs reduce shortwave absorption during the day decreasing the surface temperature and urban air temperature which leads to reduced building energy use in most US climates (Akbari and Konopacki, 2005). Bouyer et al. (2011) numerically showed the importance of considering the local condition and microclimate in building energy analysis. Radiative, conductive and convective properties of construction materials and the urban form (e.g. Krüger et al., 2010) can be engineered or selected to achieve different urban climate objectives. The effects of urban heat island mitigation measures such as increases in albedo and urban greeneries on building energy use and air quality have been investigated (e.g. Berg and Quinn, 1978; Taha et al., 1992; Rosenfeld et al., 1995; Sailor, 1995; Parker and Barkaszi, 1997; Akbari et al., 1997, 2001; Bretz et al., 1998; Akbari and Rainer, 2000; Doulos et al., 2004; Shashua-Bar et al., 2009; Scherba et al., 2011) previously. Urban planning and code development, however, often occurs with little consideration for the impacts on the atmospheric environment, and mitigation measures have heretofore been based on limited analysis of the potential suite of interacting impacts.

Consequently, urban design needs to consider these interactions and impacts of urban heat island mitigation strategies need to be analyzed carefully with appropriate modeling tools and computational resources. Just like global climate, urban climate is a complex system where changing one parameter or process will trigger positive and negative feedback effects that require holistic simulation of the physical and meteorological processes.

The success of ‘cool’ (reflective) roofs caused cool-roof building codes and incentive programs to sprout around the country (e.g. Cardin, 2011). UHI researchers and politicians now propose that reflective pavements should be the next step in reducing urban air temperatures (and associated air quality) and energy use. The Heat Island and Smog Reduction Act of 2011 (Bill H.R.51 Connolly, 2011) requires “high solar reflectivity (cool) roofs, vegetated roofs, and paving materials with higher solar reflectivity”. Assembly Bill 296 in California (Skinner, 2011) is specifically designed to advance cool pavement practices in the state and requires compilation of a Cool Pavement Handbook.

However, reflective pavements may actually increase building energy use through reflection of solar radiation onto building walls and into buildings through windows. For example, Yaghoobian et al. (2010) showed that artificial turf (the “anti-reflective pavement” with an albedo of 0.08) while being warmer than grass actually reduced local urban energy use for a San Diego building compared to grass surfaces because it reduces reflection of sunlight onto adjacent building surfaces. Pearlmutter et al. (2006) and Erell (2012) found that streets with lighter-colored walls generated a slightly higher total pedestrian heat gain, which was attributed to increased pedestrian exposure to shortwave radiation reflected from the walls. These increases outweighed the longwave radiative reductions due to lower wall temperature. Sailor’s conference presentation covered a very similar topic to the present study (Sailor, 2012).

In this paper we investigate the holistic physical interaction between buildings and the surrounding microclimate in the urban canyon. An advanced urban heat transfer/meteorological model is applied to investigate how the albedo of the canopy floor surface impacts building energy use for heating and cooling. Twenty-three different cases considering different canopy floor surface albedo and different canopy aspect ratios for two building types representing more and less energy-efficient buildings are simulated. Also the effects of window-to-wall ratio (WWR) and reflective mirrored windows are investigated. The Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES, Yaghoobian and Kleissl, 2012) is applied for these simulations. The setup of these simulations is described in Section 2. Simulation results are presented and discussed in Section 3 followed by the conclusions in Section 4.

2. Simulation setup

2.1. Temperature of urban facets indoor–outdoor building energy simulator (TUF-IOBES)

TUF-IOBES was described and validated in detail in Yaghoobian and Kleissl (2012). It is a building-to-canopy model that solves energy balance equations to simulate indoor and outdoor building surface temperatures and heat fluxes in a three-dimensional urban area. The indoor and outdoor energy balance processes are dynamically coupled taking into account weather conditions, indoor heat sources, building and urban material properties, composition of the building envelope (e.g. windows, insulation), and HVAC equipment. TUF-IOBES is also capable of simulating effects of the waste heat from air-conditioning systems on urban canopy air temperature (Yaghoobian and Kleissl, 2012). Canopy air temperature is simulated using an energy balance considering convective sensible heat fluxes from all surfaces in the canopy into the canopy air and the convective heat flux exchanged between canopy and above canopy. The latter is based on the air temperature difference between these two layers. Since the air temperature above the canopy layer is imposed as a boundary condition, it is not affected by anthropogenic heat release and the canopy air temperature; in other words it is assumed that the heat flux from inside the canopy to the atmospheric surface layer is removed from the simulation domain. A version of TUF-IOBES is employed here with outdoor convection described by the DOE-2 model (Berkeley Laboratory (LBL), 1994), the interior convection model is the ASHRAE default method, and the infiltration and ventilation model is the simple air change per hour model (Pedersen et al., 2001).

2.2. Physical building setup and thermal properties

The TMY3 weather data file for Phoenix Sky Harbor International Airport (33.45° north latitude, 111.983° west longitude and 337 m altitude) in Arizona, US, is used as forcing data at reference height. Phoenix presents an interesting case because it is a large urban development representative of the desert southwest, where reflective pavements are likely to be applied and have large effects. Also relative to other urban areas, Phoenix has a long history in urban climate research and a large body of academic work exists on the Phoenix UHI that has informed urban policy (Chow et al., 2012).

The domain geometry consists of 5 × 5 identical detached buildings and extends vertically from the deep soil to the reference height in the atmospheric surface layer (Fig. 1). Buildings have square footprints of 21.3 m on each side and heights of 18.3 m (4 storeys). Intermediate floors and internal mass are not considered. Each wall has a window centered on the wall with dimensions of 12.2 m height × 15.2 m width resulting in a window fraction of 0.47. The effects of curtains, blinds, or outside sunshades are not considered (see Section 3.3 for a detailed discussion of modeling assumptions).

Thermal properties follow prototypical post and pre-1980 office buildings suggested in Akbari and Konopacki (2005) which respectively satisfy and do not satisfy insulation requirements for nonresidential buildings in ASHRAE 90.1-2004 (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2004) (Table 1). Pre (post)-1980 buildings have R-11 (R-30) roof insulation

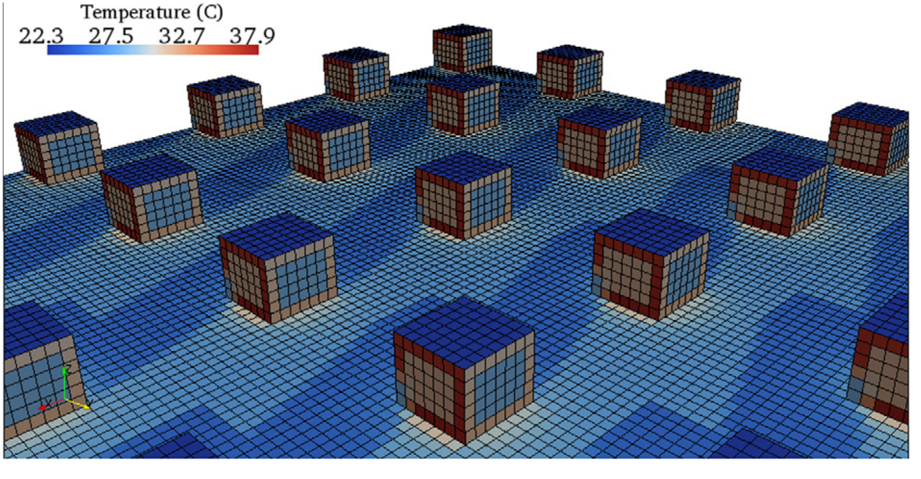

Fig. 1. Surface temperatures in the TUF-IOBES simulation domain for canopy aspect ratio of 0.37, ground surface albedo of 0.3, and pre-1980 buildings at 0600 LST of July 15th in Phoenix, AZ. The length of each patch is 3.05 m. The center 4 × 5 patches of each façade are windows.

Table 1
Building and ground material thickness, and thermal and radiative properties by layer for pre and post-1980 buildings. Properties of the single pane window are for a product named 'Clear-6/.090 PVB/Clear-6′ manufactured by 'Cardinal Glass Industries' (WINDOW v7.0.68.0, 2012). Triple pane windows are made of a clear low-e glass named 'LoE^2 240 on 6 mm Clear' manufactured by 'Cardinal Glass Industries' and 2 layers of 'Generic Clear Glass' (WINDOW v7.0.68.0, 2012). Properties of reflective windows are provided in Table A1.

Material layer	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (kJ kg^{-1} K^{-1})	Solar absorptivity [–]	IR emissivity [–]
Walls						
Brick (outside)	0.10	1.3 Incropera and Dewitt (2002)	2083 Incropera and Dewitt (2002)	0.835 Incropera and Dewitt (2002)	0.7 Oke (1987)	0.9 Oke (1987)
Insulation (R-6) (pre)	0.044	0.042[b]	32 Incropera and Dewitt (2002)	0.835 Incropera and Dewitt (2002)	–	–
Insulation (R-13) (post)	0.089	0.038[b]	32 Incropera and Dewitt, 2002	0.835 Incropera and Dewitt, 2002	–	–
Drywall-gypsum (inside)	0.013 Akbari and Konopacki (2005)	0.17 Incropera and Dewitt (2002)	800 Incropera and Dewitt (2002)	1.05 Oke (1987)	0.65[a]	0.95[a]
Roof						
Plywood	0.019 Akbari and Konopacki (2005)	0.12 Incropera and Dewitt (2002)	545 Incropera and Dewitt (2002)	1.215 Incropera and Dewitt (2002)	0.4 Akbari and Konopacki (2005)	0.9 Akbari and Konopacki (2005)
Plenum (air cavity)	0.1	0.025 The Engineering Toolbox (2012)	1.205 The Engineering Toolbox (2012)	1.005 The Engineering Toolbox (2012)	–	–
Insulation (R-11) (pre)	0.089	0.045[b]	32 Incropera and Dewitt (2002)	0.835 Incropera and Dewitt (2002)	–	–
Insulation (R-30) (post)	0.2	0.038[b]	32 Incropera and Dewitt (2002)	0.835 Incropera and Dewitt (2002)	–	–
Drywall-gypsum (inside)	0.013 Akbari and Konopacki (2005)	0.17 Incropera and Dewitt (2002)	800 Incropera and Dewitt (2002)	1.05 Oke (1987)	0.65[a]	0.95[a]
Floor						
Plywood (inside)	0.019	0.12 Incropera and Dewitt (2002)	545 Incropera and Dewitt (2002)	1.215 Incropera and Dewitt (2002)	0.8[a]	0.9 Akbari and Konopacki (2005)
Concrete	0.07	1.51 Oke (1987)	2400 Oke (1987)	0.88 Oke (1987)	–	–
Crushed rock	0.2	0.95 Crevier and Delage (2001)	1200[a]	1.05[a]	–	–
Window						
Triple-pane (post)						
Glass (clear low-E)	0.0057 WINDOW v7.0.68.0 (2012)	1.0 WINDOW v7.0.68.0 (2012)	2480 Oke (1987)	0.67 Oke (1987)	Table 2	0.84 WINDOW v7.0.68.0 (2012)

Air	0.012 WINDOW v7.0.68.0 (2012)	0.024 WINDOW v7.0.68.0 (2012)	1.292 WINDOW v7.0.68.0 (2012)	1.006 WINDOW v7.0.68.0 (2012)	–	–
Glass (clear)	0.0057 WINDOW v7.0.68.0 (2012)	1.0 WINDOW v7.0.68.0 (2012)	2480 Oke (1987)	0.67 Oke (1987)	Table 2	0.84 WINDOW v7.0.68.0 (2012)
Air	0.012 WINDOW v7.0.68.0 (2012)	0.024 WINDOW v7.0.68.0 (2012)	1.292 WINDOW v7.0.68.0 (2012)	1.006 WINDOW v7.0.68.0 (2012)	–	–
Glass (clear)	0.0057 WINDOW v7.0.68.0 (2012)	1.0 WINDOW v7.0.68.0 (2012)	2480 Oke (1987)	0.67 Oke (1987)	Table 2	0.84 WINDOW v7.0.68.0 (2012)
Single-pane (pre)						
Glass (clear)	0.0137 WINDOW v7.0.68.0 (2012)	0.617 WINDOW v7.0.68.0 (2012)	2480Oke (1987)	0.67 Oke (1987)	Table 2	0.84 WINDOW v7.0.68.0 (2012)
Ground						
Asphalt	0.07 Jansson et al. (2006)	0.75 Oke (1987)	2110Oke (1987)	0.92 Oke (1987)	0.9–0.7–0.5	0.95 Oke (1987)
Crushed rock	0.2	0.95 Crevier and Delage (2001)	1200[a]	1.05[a]	–	–

[a] Assumed.
[b] Insulation conductivities are calculated based on their typical thickness.

Table 2
Angular and diffuse Solar Heat Gain Coefficient (SHGC), absorptance and transmittance of window glass. Properties of single (triple) pane windows which are used in pre (post)-1980 buildings are simulated by WINDOW v7.0.68.0.0.68.0 software (WINDOW v7.0.68.0 (2012)).

Incident angle (degree)	SHGC (single)	SHGC (triple)	Absorptance (single)	Absorptance (triple – 1st pane)	Absorptance (triple – 2nd pane)	Absorptance (triple – 3rd pane)	Transmittance (single)	Transmittance (triple)
0	0.722	0.222	0.316	0.526	0.022	0.016	0.617	0.157
10	0.716	0.223	0.301	0.531	0.023	0.016	0.616	0.158
20	0.713	0.221	0.305	0.535	0.023	0.016	0.612	0.155
30	0.708	0.217	0.311	0.536	0.023	0.016	0.605	0.152
40	0.698	0.212	0.318	0.532	0.023	0.016	0.593	0.146
50	0.679	0.201	0.326	0.528	0.024	0.016	0.571	0.135
60	0.639	0.177	0.329	0.523	0.024	0.015	0.530	0.112
70	0.550	0.132	0.319	0.494	0.022	0.012	0.444	0.074
80	0.352	0.069	0.269	0.366	0.017	0.006	0.263	0.027
90	0	0	0	0	0	0	0	0
Diffuse	0.646	0.187	0.311	0.511	0.023	0.015	0.542	0.125

and R-6 (R-13) wall insulation. Floor construction is based on best guesses and is made of a layer of plywood over a concrete slab followed by a layer of crushed rock and is chosen the same for both types of buildings. Reflective roof surfaces are used in both building types with a solar reflectance of 0.6, i.e. re-roofing is assumed to have occurred in pre-1980 buildings. Triple-pane clear 1 Low-E layer (clear single-pane) windows with overall Solar Heat Gain Coefficient (SHGC) of 0.22 (0.72) and overall U-factor of 1.25 (5.6) W m^{-2} K^{-1} are chosen for post (pre)-1980 buildings. The triple pane windows were chosen to meet ASHRAE Standard 90.1-99 and are considered typical for new construction (Haglund, 2010). Properties of the building envelope and ground materials used in all simulations are presented in Table 1. Angular and diffuse SHGC, absorptance and transmittance of window glasses derived from the software WINDOW v7.0.68.0 (2012) are shown in Table 2.

2.3. HVAC system

In both types of buildings every day from 0600 to 1900 LST the occupancy is 75 persons per floor (0.16 person m^{-2}) and internal loads from lighting and equipments are 15.1 W m^{-2} and 16.1 W m^{-2} of floor area. Continuous HVAC operation is assumed. The heat transfer to/from the HVAC system satisfies the air heat balance (the convective heat transfer from the zone surfaces, convective contribution of internal loads, and the sensible load due to infiltration and ventilation) to keep the room air temperature between 21.1 °C and 25.6 °C heating and cooling setpoints (Chamberlin and Schwenk, 1994), respectively. The air conditioning equipment is chosen as 'air conditioners, air cooled' based on Akbari and Konopacki (2005). Since in ASHRAE 90.1-2004 the required 'minimum efficiency' is 10.1 and 10.3 EER (~2.9 and 3.0 COP), the Coefficient of performance (COP) of the cooling system in both types of buildings is chosen as 2.9 consistent with Akbari and Konopacki (2005) for post-1980 buildings. An efficiency of 1 is assumed for the (electric) heating supply. Using ANSI/ASHRAE Standard 62.1-2007 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007) (outdoor air rate in office spaces of 0.0023 m^3 s^{-1} $person^{-1}$ people and 3.04×10^{-4} m^3 s^{-1} m^{-2} area) the minimum required outdoor airflow in both types of buildings is 0.55 air changes per hour (ACH).

2.4. Scenarios for ground surface albedo, canopy aspect ratio, and window fraction

To study the interactive effects of different urban mitigation strategies on building energy use three different canopy aspect ratios (the building height (H) divided by the distance between buildings (W)) (0.37, 1.0, 1.5) in both x and y directions and three different canopy ground surface albedos (0.1, 0.3, 0.5) are used while the building wall albedo is kept constant at 0.3. Canopy aspect ratio directly and non-linearly modulates the effect of reflective pavements so the two parameters have to be investigated jointly. Increased shading for large aspect ratios makes reflective materials less effective. The ground surface albedo choices are motivated by data from the Concrete Pavement Association

(American Concrete Pavement Association, 2002) for weathered materials: asphalt 0.1–0.15; gray portland cement concrete 0.2–0.3; white portland cement concrete 0.4–0.6.

To study the effects of window to wall fraction which varies significantly in office buildings, a sensitivity test for the case with $H/W = 1$ and ground surface albedo of 0.5 is conducted considering a smaller (0.24) and a larger (0.66) window to wall fraction. Also since many office buildings have reflective mirrored windows, for one case in a canopy with $H/W = 0.37$ and ground surface albedo of 0.5 the effects of double-pane reflective mirrored windows are compared with the triple-pane clear windows in post-1980 buildings. The overall SHGC of the reflective window is chosen to be close to that of typical reflective windows in Phoenix, AZ (Haglund, 2010) (Table A2).

3. Results and discussion

3.1. Annual and daily thermal loads

Fig. 2 shows annual thermal loads of post and pre-1980 buildings (representing energy efficient and less energy efficient buildings representative of the building stock) versus ground surface solar

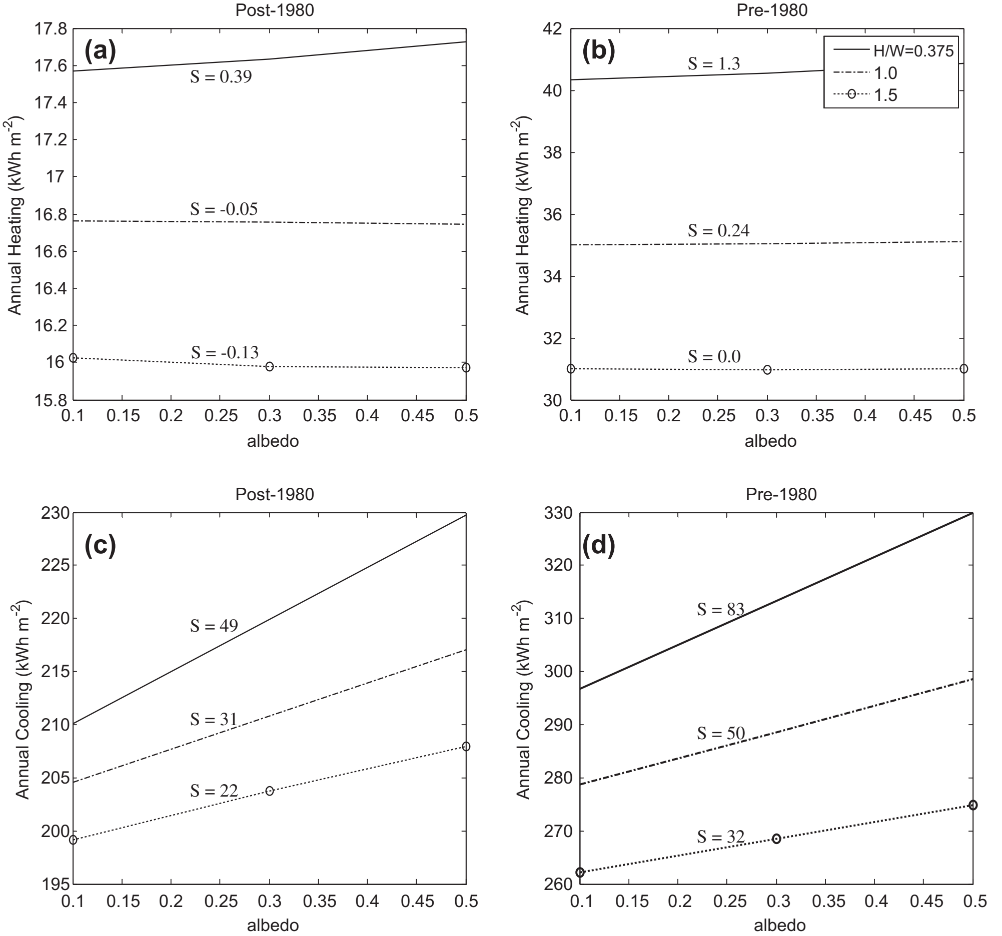

Fig. 2. Annual heating and annual cooling loads for post (a and c) and pre (b and d) 1980 buildings in Phoenix, AZ. *S* is the slope of annual thermal load with respect to ground surface albedo in units of kWh m^{-2} per albedo change from 0 to 1.

Table 3
Annual heating and annual cooling loads for all cases with ground surface albedo of 0.5.

	Simulation type (ground albedo = 0.5)	Annual heating load (kWh m^{-2})	Annual cooling load (kWh m^{-2})
Pre-1980 buildings	H/W = 0.37, WWR = 0.47	40.8	329.8
	1.0, 0.47	35.1	298.6
	1.5, 0.47	30.9	274.8
	1.0, 0.24	24	248.9
	1.0, 0.66	45.1	326
Post-1980 Buildings	H/W = 0.37, WWR = 0.47	17.7	229.7
	1.0, 0.47	16.7	217
	1.5, 0.47	15.9	207.9
	1.0, 0.24	14.6	190.3
	1.0, 0.66	18.7	237.4
	0.37, 0.47, Reflective window	21.1	219.4

reflectance for three different canopy aspect ratios. Table 3 shows the annual heating and cooling loads for all scenarios with ground surface albedo of 0.5. As expected, for both types of buildings annual heating and annual cooling loads decrease with increasing canopy height-to-width ratio (H/W). Also annual thermal loads increase with increasing WWR. On the other hand annual cooling noticeably increases in both types of buildings with increasing ground surface albedo, but annual heating shows little or no sensitivity to ground surface albedo. The next sections will analyze these results in more detail.

3.1.1. Canopy floor surface albedo

Fig. 2 indicates that for both pre and post-1980 buildings and for all three canopy aspect ratios annual thermal loads change linearly with ground surface albedo, albeit the sensitivity (i.e. the slope in Fig. 2) is different. Due to larger conduction (because of poor insulation) and larger transmitted shortwave radiation (due to single-pane windows) the thermal demand in pre-1980 buildings is more sensitive to canopy floor albedo.

To better understand how the annual (and peak) simulation results relate to the thermal processes, Figs. 3 and 4 present monthly average diurnal cycle results for the average July day including temperatures of ground surface, canopy air, outside building wall including windows, inside building surfaces with the total transmitted shortwave radiation into the building from all windows and thermal loads. The average wind speed in July is 3.6 m s^{-1} and average daily high and low air temperatures are 41.4 °C and 29.9 °C, respectively. Since the heating/cooling load change with albedo was linear, only the 0.1 and 0.5 ground surface albedo simulations are shown.

As expected, during the day the temperature of the darker ground surface is significantly higher than the temperature of the brighter surface (differences up to 15.8 °C at 14 LST for canopies with H/W = 0.37; Figs. 3a and 4a). This temperature difference affects air temperature in the canopy but this effect is relatively small (0.4 °C at 14 LST for canopies with H/W = 0.37; Figs. 3b and 4b). The effects of ground surface albedo on canopy air temperature are larger in canopies with smaller aspect ratios.

Larger ground albedo results in larger shortwave reflection onto the wall and window surfaces and larger transmitted shortwave radiation into the buildings (Figs. 3e and 4e) causing higher indoor surface temperatures (Figs. 3d and 4d) and decrease in heating load (winter; not shown) and increase in cooling load (summer; Figs. 3f and 4f). Similar processes (at different magnitudes) can be observed for a typical winter day (not shown).

3.1.2. Canopy aspect ratio

The slope of annual thermal loads with respect to ground surface albedo (Fig. 2) and the diurnal cycles (Figs. 3 and 4) indicate that (as expected) the albedo effect is stronger for smaller H/W. The thermal conditions and indoor–outdoor heat fluxes converge with increasing H/W since in deep and narrower canopies less shortwave radiation reaches the ground surface making the ground surface albedo less relevant. In addition, due to shadowing during the day the ground, outdoor and indoor building

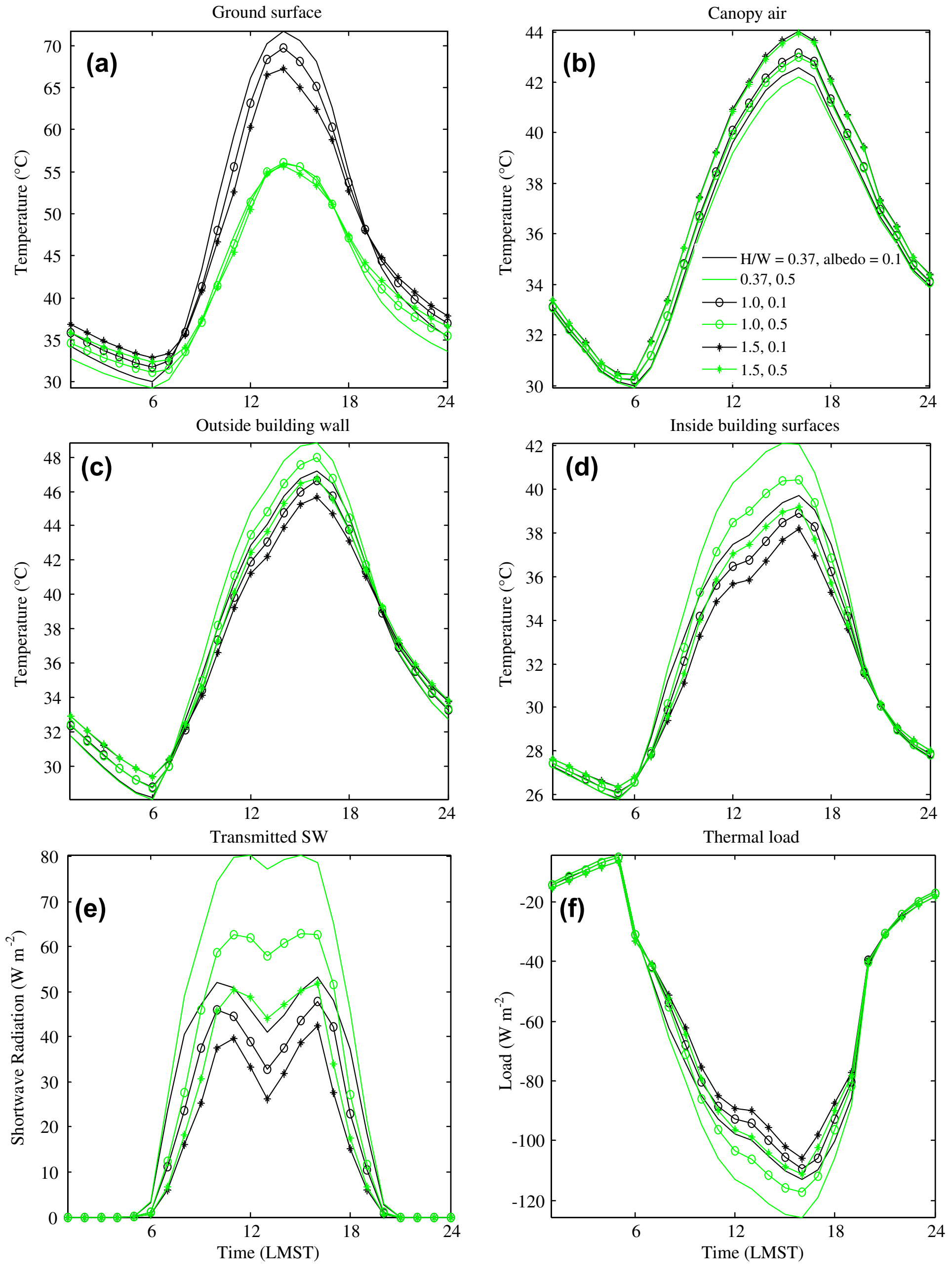

Fig. 3. Comparison of monthly averaged (a) ground surface, (b) canopy air, (c) outdoor wall surface, (d) indoor building surface temperatures, (e) total transmitted shortwave radiation into the building from all windows and (f) thermal loads for pre-1980 buildings for July in Phoenix, AZ. Transmitted shortwave radiation and thermal loads are in Watt per square meter of floor area. Outside building wall temperature is averaged over all four outside walls including windows. Indoor building surface temperature is the average temperature of all surface temperatures inside the building.

surface temperatures decrease with increasing canopy H/W (Figs. 3 and 4a, c and d). The reverse trend is observed at night when the reduction in longwave radiation losses at the outside surfaces leads to

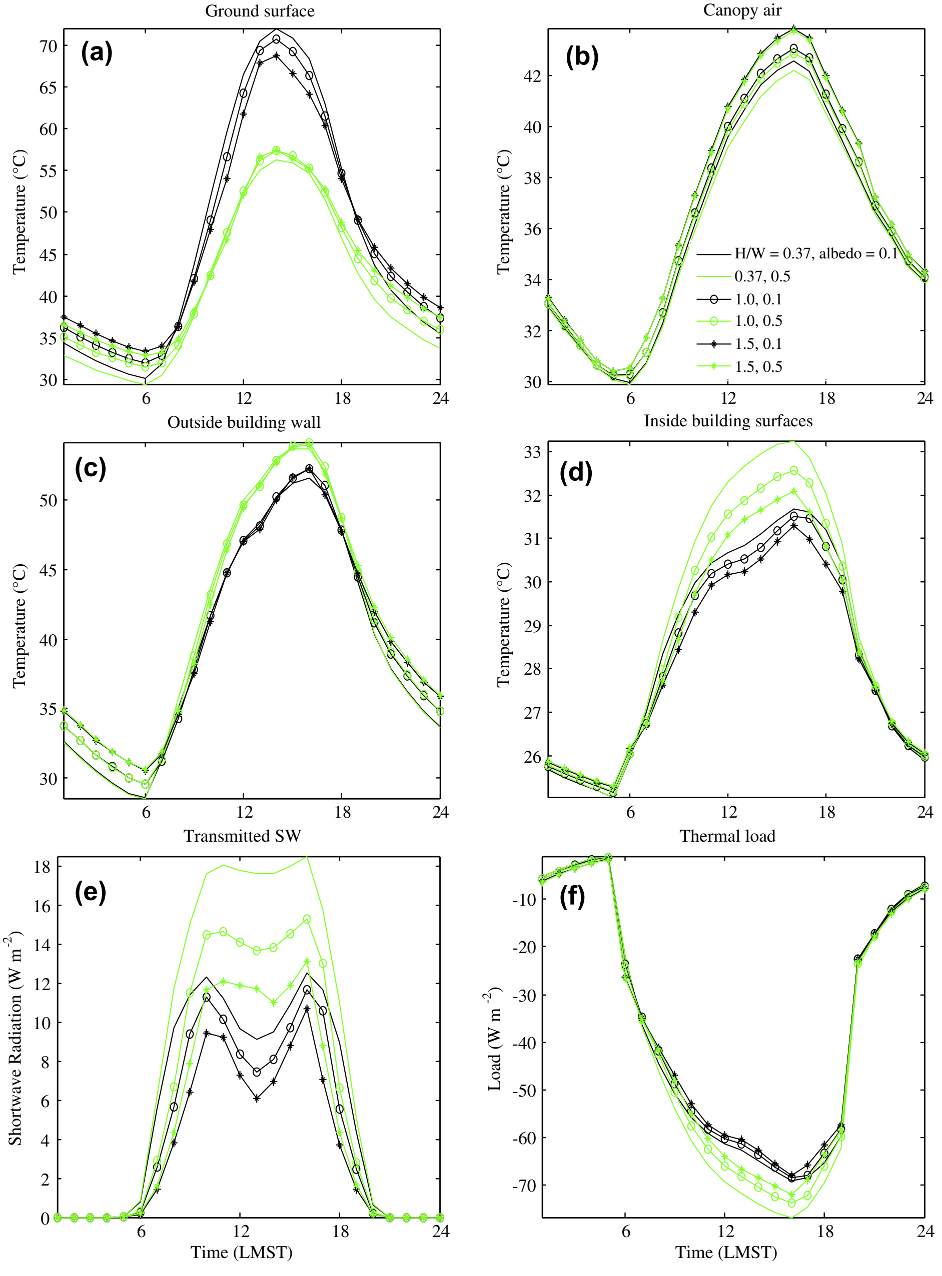

Fig. 4. Comparison of monthly averaged (a) ground surface, (b) canopy air, (c) outdoor wall surface, (d) indoor building surface temperatures, (e) total transmitted shortwave radiation into the building from all windows and (f) thermal loads for post-1980 buildings for July in Phoenix, AZ. Transmitted shortwave radiation and thermal loads are in Watt per square meter of floor area. Outside building wall temperature is averaged over all four outside walls including windows. Indoor building surface temperature is the average temperature of all surface temperatures inside the building.

increased air and surface temperatures for larger H/W. The reduction of turbulent sensible heat transfer out of the canyon also contributes to increased air temperature in canopies with larger H/W (Oke et al., 1991; Oke, 1988).

As a result of less transmitted shortwave radiation into the buildings in deep and narrower canopies less (mostly daytime) cooling is required with increasing H/W (Figs. 3f and 4f) in both types of buildings.

3.1.3. Building condition and construction materials

In both pre and post-1980 buildings, heating mostly occurs at night and cooling mostly happens during the day due to solar and internal heat gains. Due to poor insulation (in walls and single pane windows), the indoor air and surface temperatures of pre-1980 building are strongly influenced by the outdoor temperatures. Comparing the annual thermal loads (Fig. 2 and Table 3) reveals that pre-1980 buildings require more heating and cooling energy than post-1980 buildings. On the other hand, in post-1980 buildings due to stronger insulation the conductive heat exchange between indoor and outdoor is smaller. Consequently at night the inside environment does not benefit much from the higher outdoor temperature in larger H/W to reduce heating loads and as a result the maximum difference in annual heating loads for small and large H/W is small (<1.8 kWh m^{-2}) for post-1980 buildings (Fig. 2a).

Figs. 3c and 4c (average outdoor surface temperature of walls and windows) show that for a typical summer day the outside building surface temperature in a post-1980 building is generally higher than in a pre-1980 building. The lower outdoor building surface temperature in pre-1980 buildings can be explained by larger heat conduction into the building through walls and single-pane windows due to smaller thermal resistances compared to the well insulated walls and triple-pane windows in post-1980 buildings.

Indoor building surface temperature is a result of heat transferred into the building through the building envelope, transmitted shortwave radiation, radiation and convection from internal loads and indirect effects of infiltration and ventilation. With the same amount of internal loads and infiltration/ventilation in both types of buildings, the larger transmitted shortwave radiation through single pane windows and larger heat transfer through the building walls and roof in pre-1980 buildings cause indoor surfaces to experience higher temperatures.

3.1.4. Window type and size effects

3.1.4.1. Single versus triple-pane window. As shown in Figs. 3e and 4e, there is a large difference between transmitted shortwave radiation through single-pane windows in pre-1980 buildings and triple-pane windows in post-1980 buildings (a factor of 5). Triple and single-pane windows have very different thermal and radiative properties (Tables 1 and 2). A triple-pane window with two air gaps provides stronger insulation reducing the conductive heat transfer. In addition, triple-pane windows have larger absorptance and smaller SHGC and transmittance. As a result conductive heat gain and transmitted shortwave radiation into the building noticeably decrease compared to the buildings with single-pane windows reducing cooling demand. Fig. 5 displays the comparison of transmitted shortwave radiation (in W m^{-2} of floor area) through single and triple-pane windows and total thermal loads of pre and post-1980 buildings for canopies with $H/W = 1$ and ground surface albedo of 0.5 for a typical summer day. The ratio of the total amount of transmitted shortwave radiation through single-pane windows in pre-1980 buildings to the total cooling load can be up to 68% at 10 LST compared to 25% of triple-pane windows in post-1980 building at the same time. The daily integrated value of transmitted shortwave radiation and cooling load for a typical summer day in pre-1980 building are 606 and 1406.1 Wh m^{-2} of floor area and in post-1980 buildings are 144.3 and 907.5 Wh m^{-2} of floor area, respectively. This indicates the importance of the window properties and the effects of outdoor conditions on the available shortwave radiation incident on a building on the building thermal loads.

3.1.4.2. Reflective mirrored windows. Fig. 6 compares the effects of typical reflective windows on transmitted shortwave radiation into the building and thermal load for average summer and winter days in Phoenix, AZ. As expected a clear window transmits more shortwave radiation into the building than a reflective window (Fig. 6a and c). The difference in thermal loads results from the differences in the overall window conductivity and transmittance (that are lumped in the SHGC). While the transmittance and SHGC of the double-pane reflective windows is even smaller than the triple-pane windows in post-1980 buildings (Table 2 and Table A2), the conductivity of double pane windows is larger.

Consequently, during the summer (Fig. 6b) even though there is less transmitted shortwave radiation into the building through reflective double-pane windows there is a small difference between cooling loads; during 13–17 LST the cooling load in the building with the reflective window is even larger than the building with triple-pane clear window. The reason is that heat conduction (large temperature difference between indoors and outdoors) then dominates over light transmission. On the other hand when indoor-outdoor temperature gradients are reversed (winter), besides less transmitted shortwave radiation into the building, buildings with double-pane reflective windows also benefit from outdoor cool air in winter and so daytime cooling load in these buildings is less than for triple-pane clear windows (total of 0.05 kWh m^{-2} in a typical winter day). During winter nights, however, the difference in heating loads in Fig. 6d is only related to the difference in window conductivity. The annual cooling load in buildings with double-pane reflective windows is 4.5% (10.3 kWh m^{-2}) less than in buildings with triple-pane clear windows but the annual heating load is 19.2% (3.4 kWh m^{-2}) larger (Table 3). Another reason for the relatively small relative differences in cooling load is that there is a negative feedback in that the energy reflected from reflective windows increase the amount of available radiation reaching the surrounding building walls and ground surfaces and affects the thermal load in adjacent buildings.

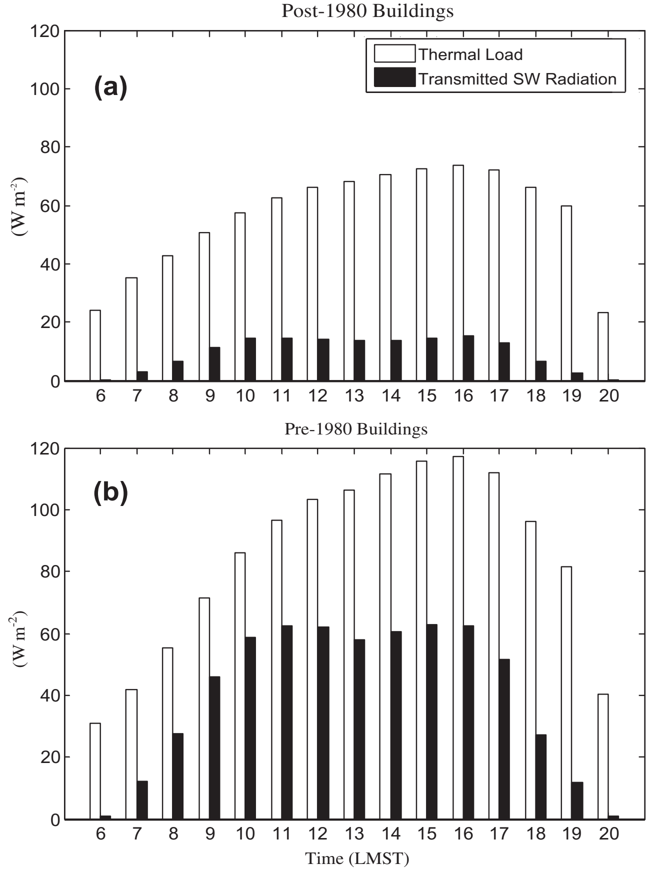

Fig. 5. Comparison of the transmitted shortwave radiation through windows and total thermal load of (a) post and (b) pre-1980 buildings in W m^{-2} of floor area for canopies with H/W = 1 and ground surface albedo of 0.5 for a typical summer day (monthly averaged diurnal cycle over July) in Phoenix, AZ.

3.1.4.3. Window surface area. Besides window type, window size is the other important factor in controlling indoor temperatures and thermal demand in buildings. The main impact of larger windows in our study is that they transmit more shortwave radiation into the building resulting in larger surface and air temperatures. Larger windows also cause more conductive exchange between indoors and outdoors, due to their larger thermal conductivity compared to walls. Fig. 7 shows transmitted shortwave radiation through windows and thermal loads in buildings with three different WWRs for a typical summer day. Increasing WWR from 0.24 to 0.66 (for post-1980 buildings in canopies with $H/W = 1$ and ground surface albedo of 0.5) results in a 20% increase in total daily cooling demand for a typical summer day and 25% (28%) increase in total annual cooling (heating) demand. The same trends for WWR exist for pre-1980 buildings and for winter times. While increased shortwave transmission for large WWR acts to reduce heating loads in the winter, most heating happens at night and then the larger conductivity of windows versus walls leads to an overall increase in heating loads (not shown).

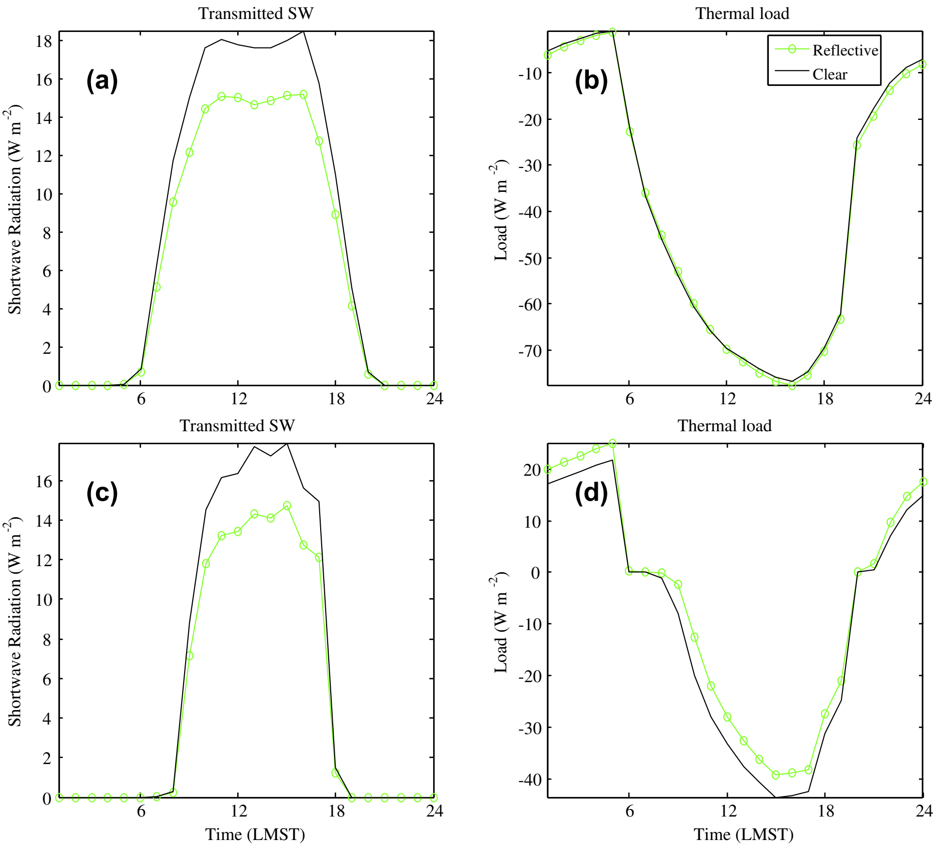

Fig. 6. Comparison of monthly averaged total transmitted shortwave radiation into the building from all windows (a and c) and thermal loads (b and d) in post-1980 buildings with double-pane reflective windows and triple-pane clear windows in July (a and b) and January (c and d) in a canopy with $H/W = 0.37$ and ground surface albedo of 0.5. Negative (positive) loads represent cooling (heating). Transmitted shortwave radiation and thermal loads are in Watt per square meter of floor area.

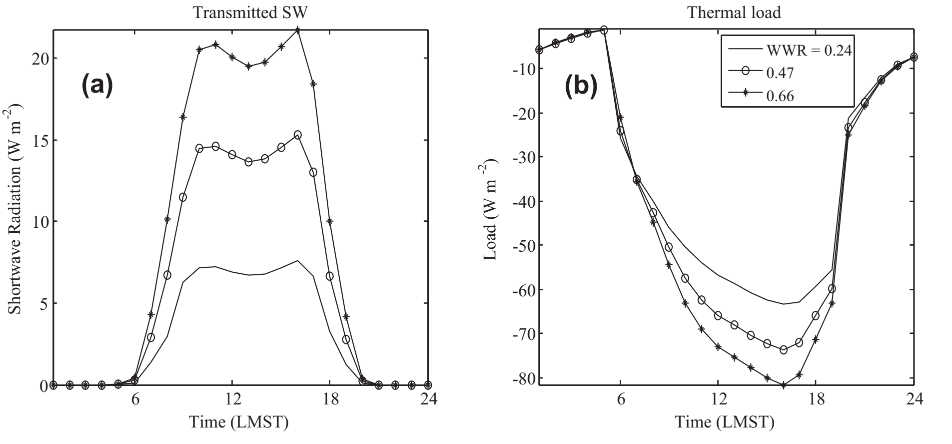

Fig. 7. Comparison of monthly averaged (a) total transmitted shortwave radiation into the building from all windows and (b) thermal loads for post-1980 buildings in canopies with $H/W = 1$ and ground surface albedo of 0.5 for July in Phoenix, AZ for three different window-to-wall ratios (WWR). Transmitted shortwave radiation and thermal loads are in Watt per square meter of floor area.

3.2. Peak thermal loads

Peak thermal loads are important because they determine sizing of the HVAC system. Peak loads also typically occur during clear days with large insolation amplifying the effects of reflective pavements. Fig. 8 shows the change in annual peak thermal loads of post and pre-1980 buildings with respect to change in ground surface albedo for three different canopy aspect ratios. The trend of peak thermal loads is similar to the trend of annual thermal loads and can be explained similarly. Generally, buildings in denser neighborhoods (larger H/W) require smaller HVAC systems. Not surprisingly, Fig. 8 also shows that peak heating loads in both types of buildings are independent of canopy floor albedo since they occur at night. With increasing ground surface albedo from 0.1 to 0.5 peak cooling demand increases by 5.3–10.6% (6–13 W m^{-2}) in pre-1980 buildings and 7.1–10.9% (5.2–8 W m^{-2}) in post-1980 buildings. The relative changes are similar in magnitude to the annual cooling load changes with albedo. HVAC systems have to be larger in pre-1980 buildings since all peak cooling load components are larger than in post-1980 buildings.

3.3. Discussion of modeling assumptions

Effects on building energy use in the immediate vicinity of high albedo pavements through radiative and conductive increases in cooling load (Figs. 3 and 4c–e) by far dominate indirect effects through reduction in canopy air temperature (Figs. 3b and 4b). Canopy air temperature is more sensitive to the canopy aspect ratio than ground surface albedo. However, our simulations assume perfect advection, i.e. the heat flux from inside the canopy to the atmospheric surface layer is removed from the simulation domain. Consequently, feedback effects acting on air temperature are blunted compared to simulations with one dimensional atmospheric models including the boundary layer and recirculating flow (e.g. Krayenhoff and Voogt, 2010). Accounting for the non-local effect of a larger reflective pavement program in an urban area would reduce (but not reverse) the increase in energy use with increasing albedo. Similarly, since there is no coupling between the canopy and atmospheric surface layer, in TUF-IOBES roof thermal behavior is independent of canopy aspect ratio and ground surface albedo.

While we also ignore the high pavement albedo effects on the earth's radiative balance and reduction in global warming, this feedback on building energy use is small.

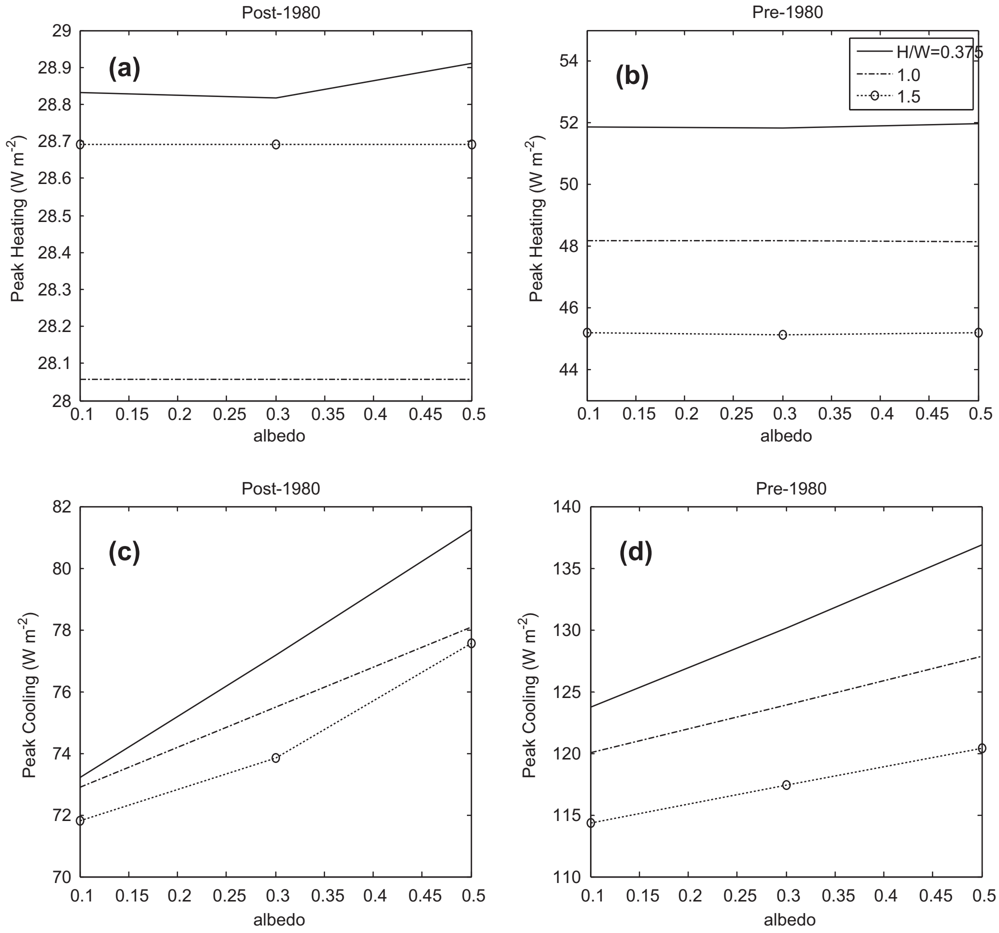

Fig. 8. Peak heating and peak cooling loads over a year for post (a and c) and pre (b and d) 1980 buildings in Phoenix, AZ.

The magnitude of simulated heating loads is unrealistic for commercial buildings since HVAC systems do not operate at nights. Furthermore, considering intermediate floors and associated thermal mass in these simulations would reduce the daytime and increase the nighttime cooling loads; however sensitivity studies (not shown) demonstrated minimal changes in annual and peak cooling loads. During peak days the thermal mass is already warm due to heat storage on previous days limiting its thermal impacts on indoor air compared to a simulation without thermal mass.

Since canopy aspect ratio and ground surface albedo affect natural lighting in buildings, they also affect building energy use for lighting (Strømann-Andersen and Sattrup, 2011). For example, in denser neighborhoods or over darker ground surfaces more artificial lighting and consequently more energy should be required in buildings. Besides the parameters modeled in this study (shadowing of neighboring buildings for large H/W and multi-pane windows with different size and radiative properties, Table 2 and Table A2), transmitted solar radiation depends on shading devices (curtains, blinds or outside sunshades (Akbari, 2002) and window locations. Moreover, lighting in most office buildings is not controlled dynamically based on photo-cells and human operator action is unlikely. Also for visual comfort of pedestrians and vehicle operators a significant fraction of the albedo gain of very reflective pavements would be achieved in the near-infrared spectrum. Increase in near-infrared irradiation indoors would not cause any change in artificial lighting needs. Properly accounting for energy implications of indoor light conditions would require modeling spectral irradiance, glare and shading devices, and the human intervention. Since these interactions are complex to model and the impacts are likely small, we neglect the feedback effect of improved daylighting for more reflective ground surfaces.

4. Conclusion

The Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES) is applied to investigate the effects of reflective pavements on energy use in nonresidential office buildings in Phoenix, AZ. Sensitivity of the results to canopy aspect ratio, building age (as reflected in insulation), window surface area, and windows with different radiative properties are also investigated. The results of this study show that the annual thermal loads decrease with increasing canopy height-to-width ratio and increase with increasing window-to-wall ratio. On the other hand annual cooling increases with increasing ground surface albedo but annual heating shows no sensitivity to ground surface albedo. The effect of double-pane reflective windows compared to triple-pane clear windows on building energy use is to decrease the annual cooling load and increase the annual heating load.

As also highlighted by Bouyer et al. (2011) and Strømann-Andersen and Sattrup (2011), our results indicate the importance of the direct evaluation of the microclimate influence (e.g. effects of canopy floor reflectance and urban canopy height to width ratio) on building energy use. The diversity of urban landscapes and designs means that an idealized study such as ours cannot provide optimum solutions for size and type of the building elements or shape of urban canopies. Only local simulations for specific neighborhoods and urban climates can elucidate the exact effect of reflective pavement implementation. For example, energy use in older buildings in New York City, even those dating to the early 1900s, is less than in most new structures because of fewer windows and thicker walls used in the older structures (Navarro, 2012).

Strømann-Andersen and Sattrup (2011) investigated the effects of the solar radiation distribution and daylight on total energy use (heating, cooling, and artificial lighting) in canopies with different aspect ratios for the urban morphology of Copenhagen. In their study artificial lighting is the dominant contributor to energy use. Energy use for artificial lighting increases more than six times at $H/W = 3$ compared to an unobstructed building. Consistent with our results, Strømann-Andersen and Sattrup (2011) show that cooling demand decreases with increasing canopy aspect ratio due to overshadowing.

This study shows that the interaction of urban materials like reflective pavements and mirrored windows with surrounding buildings must be considered in the context of an urban area. The increase in energy use for buildings near reflective pavements shown in this paper for a typical scenario indicates that reflective pavements should be considered with caution. On the other hand, application of cool pavement to roads without nearby air-conditioned buildings reduces global radiative forcing counteracting global warming (Akbari et al., 2009) and reduces air temperatures and energy use in urban areas downwind. We recommend that policymakers carefully weigh the benefits and disadvantage of reflective pavements to ensure their optimal application.

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Appendix A

See Tables A1 and A2.

Table A1
Double-pane reflective window thickness and thermal properties by layer. Properties of the reflective glass are for a product named 'Solar Silver 20% on 3 mm Clear' manufactured by 'Johnson laminating & Coating Inc.' (WINDOW v7.0.68.0 (2012)). Properties of the clear glass are for a product named 'Clear-6/.090 PVB/Clear-6′ manufactured by 'Cardinal Glass Industries' (WINDOW v7.0.68.0 (2012)).

Double-pane reflective window	Thickness (m)	Conductivity ($W\ m^{-1}\ K^{-1}$)	Density ($kg\ m^{-3}$)	Specific heat ($kJ\ kg^{-1}\ K^{-1}$)	IR emissivity [–]
Glass (reflective)	0.0032 WINDOW v7.0.68.0 (2012)	0.969 WINDOW v7.0.68.0 (2012)	2480 Oke (1987)	0.67 Oke (1987)	0.84 WINDOW v7.0.68.0 (2012)
Air	0.012 WINDOW v7.0.68.0 (2012)	0.024 WINDOW v7.0.68.0 (2012)	1.292 WINDOW v7.0.68.0 (2012)	1.006 WINDOW v7.0.68.0 (2012)	–
Glass (clear)	0.013 WINDOW v7.0.68.0 (2012)	0.617 WINDOW v7.0.68.0 (2012)	2480 Oke, 1987	0.67 Oke, 1987	0.84 WINDOW v7.0.68.0 (2012)

Table A2
Angular and diffuse Solar Heat Gain Coefficient (SHGC), absorptance and transmittance of double-pane reflective window. Properties of the window are simulated by WINDOW v7 software (WINDOW v7.0.68.0 (2012)).

Incident angle (degree)	SHGC	Absorptance (reflective pane)	Absorptance (clear pane)	Transmittance
0	0.197	0.315	0.044	0.123
10	0.198	0.318	0.045	0.123
20	0.196	0.321	0.045	0.121
30	0.194	0.322	0.045	0.118
40	0.190	0.320	0.045	0.114
50	0.182	0.317	0.045	0.108
60	0.167	0.314	0.043	0.094
70	0.136	0.297	0.037	0.070
80	0.080	0.222	0.025	0.033
90	0	0	0	0
Diffuse	0.172	0.307	0.042	0.101

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