View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by KU ScholarWor

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L03701, doi:10.1029/2009GL042194, 2010

Click Here for Full Article

Effects of white roofs on urban temperature in a global climate model

K. W. Oleson,[1] G. B. Bonan,[1] and J. Feddema[2]

Received 18 December 2009; accepted 4 January 2010; published 3 February 2010.

[1] Increasing the albedo of urban surfaces has received attention as a strategy to mitigate urban heat islands. Here, the effects of globally installing white roofs are assessed using an urban canyon model coupled to a global climate model. Averaged over all urban areas, the annual mean heat island decreased by 33%. Urban daily maximum temperature decreased by 0.6°C and daily minimum temperature by 0.3°C. Spatial variability in the heat island response is caused by changes in absorbed solar radiation and specification of roof thermal admittance. At high latitudes in winter, the increase in roof albedo is less effective at reducing the heat island due to low incoming solar radiation, the high albedo of snow intercepted by roofs, and an increase in space heating that compensates for reduced solar heating. Global space heating increased more than air conditioning decreased, suggesting that end-use energy costs must be considered in evaluating the benefits of white roofs. **Citation:** Oleson, K. W., G. B. Bonan, and J. Feddema (2010), Effects of white roofs on urban temperature in a global climate model, *Geophys. Res. Lett.*, *37*, L03701, doi:10.1029/2009GL042194.

1. Introduction

[2] An analysis by *Akbari et al.* [2009] indicated that increasing the albedo of urban roofs and pavements globally could produce a negative radiative forcing equivalent to a 44 Gt CO_2 emission offset. This is equivalent to offsetting the effect of the growth in CO_2-equivalent emission rates for the next 11 years. It was also noted that potential energy savings may be realized due to a reduction in the amount of energy consumed by air conditioning to cool buildings. The effects of increasing the albedo of cities on near-surface climate, in particular air temperature, were not addressed.

[3] Surfaces with higher albedo reflect more solar radiation, thereby decreasing surface temperature and heating of the surrounding air. Several studies have quantified the ability of increases in albedo to mitigate the urban heat island and decrease cooling energy use. Generally, these have been conducted with mesoscale weather models applied to individual cities using large-scale albedo changes (i.e., changing the albedo of entire cities). *Sailor* [1995] showed that increasing the albedo in Los Angeles decreased peak summertime temperatures by as much as 1.5°C. *Taha et al.* [1999] showed that large-scale increases in surface albedo for ten cities in the U.S. reduced the near-surface daytime summer air temperature by 0.5 to 1.5°C and decreased peak electricity demand by up to 10%. *Synnefa et al.* [2008] found that large-scale increases in roof albedo decreased the summer heat island intensity in Athens, Greece by 1–2°C on average.

[4] Here, we examine the impact of an increase in roof albedo on near-surface urban climates using an urban canyon model coupled to a global climate model. The primary purpose of the urban canyon model is to provide an estimate of near-surface air temperature for urban areas, which is where most people live. Although the influence of urban areas on large-scale climate is small, a coupled modeling approach allows assessment of the impacts of changing climate on urban populations and exploration of climate change mitigation options. The purpose of this study is to highlight issues with heat island mitigation using white roofs and to identify what processes must be considered when evaluating the effectiveness of this urban heat island mitigation method.

[5] The canyon model allows us to make changes in roof albedo only, rather than city-wide changes. In contrast to *Akbari et al.* [2009], who increased the albedo of roofs and pavement, we modified only roof albedo because roofs comprise about 40% of the global urban horizontal surfaces in the model while the impervious pavement is only about 15% of the urban surface (T. Jackson et al., Parameterization of urban characteristics for global climate modeling, submitted to *Annals of the Association of American Geographers*, 2009). Thus, changing roof albedo should have the largest impact on near-surface urban climate. The urban model also estimates large-scale space heating and air conditioning (HAC) fluxes by controlling internal building temperatures within specified comfort levels. The effect of increased albedo on these fluxes is also quantified.

2. Data and Methods

[6] The urban canyon model CLMU [*Oleson et al.*, 2008a, 2008b] is coupled to the Community Land Model version 3.5 (CLM3.5) [*Oleson et al.*, 2008c] and the Community Atmosphere Model version 3.5 (CAM3.5) [*Neale et al.*, 2008], which are the land and atmospheric components of the Community Climate System Model (CCSM) [*Collins et al.*, 2006]. The canyon system consists of roofs, walls, and canyon floor. Walls are divided into shaded and sunlit components. The canyon floor is divided into pervious (greenspace) and impervious (pavement) fractions. The urban components are arranged in an "urban canyon" configuration [*Oke*, 1987] in which the canyon geometry is described by building height and street width. The boundary conditions for heat transfer within roofs and walls are determined by an interior building temperature held between prescribed minimum and maximum temperatures, thus explicitly resolving HAC fluxes. Sources of waste heat from inefficiencies in the HAC systems are incorporated as terms in the canyon energy budget. The heat and moisture

---

[1] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA.

[2] Department of Geography, University of Kansas, Lawrence, Kansas, USA.

Copyright 2010 by the American Geophysical Union.

0094-8276/10/2009GL042194$05.00

fluxes from each surface (including the roof) interact with each other through a bulk air mass that represents air in the urban canopy layer. The urban model produces turbulent, momentum, and radiative fluxes which are area-averaged with fluxes from non-urban surfaces (e.g., vegetation and lakes) to supply grid cell averaged fluxes to the atmospheric model. The version of CLMU used here is the same as that used by *Oleson et al.* [2008a] but with improvements to the pervious greenspace hydrology and a revised treatment of HAC and waste heat fluxes that results in a more stable numerical solution (see Text S1 of the auxiliary material).[1]

[7] Urban areas are prescribed from a dataset of present day urban extent and urban properties [*Jackson et al.,* 2009]. In the dataset, urban extent for four density classes was derived from the LandScan 2004 population density dataset [*Dobson et al.*, 2000]. For each of 33 regions across the globe, thermal (e.g., heat capacity and thermal conductivity), radiative (e.g., albedo and emissivity), and morphological (e.g., height to width ratio, roof fraction, average building height, and pervious fraction of canyon floor) properties of the roof/wall/road system are provided. Building interior minimum and maximum temperatures are based on climate and socioeconomic considerations. Urban extent in these simulations is the sum of three density classes: tall building district, high density, and medium density. Urban properties are from the dominant density type by area, which is almost exclusively medium density (see Figure S1 of the auxiliary material).

[8] Two climate simulations were run from 1941 to 1999 at a spatial resolution of 1.9° latitude by 2.5° longitude. Sea surface temperatures, sea-ice, and greenhouse gases (CO_2, CH_4, N_2O, and CFCs) are prescribed for 1941–1999 from an IPCC Fourth Assessment Report [*Intergovernmental Panel on Climate Change*, 2007] 20th century CCSM3 ensemble member. The first simulation (CON) is a control that uses the standard urban surface dataset described above. The second simulation (ALB) increases the albedo of roofs to 0.9, the maximum albedo of a white coating covering an entire roof (Energy Star, Roof product list, 2008, available at http://www.energystar.gov/ia/products/prod_lists/roofs_prod_list.pdf). This albedo could not be practically achieved due to aging effects, obstructions and openings on the roof surface (e.g., heating and cooling vents), and logistical and financial considerations. However, the purpose here is to provide a large perturbation to the model to assess the relative importance of roofs in the global urban energy budget.

[9] In addition, three 10-year global offline (i.e., uncoupled from the atmospheric model) simulations were performed. The first (CON_O) and second (ALB_O) simulations were configured the same as the CON and ALB simulations except that atmospheric forcing for both simulations was provided by repeating year 2000 from *Qian et al.*'s [2006] meteorological dataset as described by *Oleson et al.* [2008c]. These two simulations isolate the effects of white roofs under identical atmospheric forcing derived from reanalysis products. This provides an assessment of the effects of internal variability and biases in the coupled model climate on the results. The third simulation (CON_O_NHAC) is the same as CON_O except that HAC and waste heat fluxes are excluded to illustrate the influence of these fluxes on the heat island under identical atmospheric forcing.

3. Results

[10] Because of the coarse spatial resolution of these simulations, the urban fractions within the model grid cells are small and there are no statistically significant changes in grid cell average surface climate caused by the increase in roof albedo (not shown). Modification to roof albedo primarily affects the near-surface urban climate. The urban heat island is defined at each model grid cell containing urban area by comparing the air temperature in the urban canopy layer to the 2-m air temperature from the "rural" surfaces (i.e., the vegetated and bare soil surfaces) in the grid cell. Increasing the roof albedo decreases the annual mean heat island in nearly every grid cell that has urban area (Figure 1). Averaged over all urban areas resolved in the model, the annual mean heat island in the CON simulation is about 1.2°C. This is decreased by about 33% to 0.8°C in the ALB simulation.

[11] An example of how the increase in roof albedo affects the urban energy budget and the urban-rural contrast in air temperature is shown in Figure 2. The grid cell illustrated here includes New York City. The urban-rural contrasts in air temperature and energy balance in the control simulation are typical of how the model represents these surfaces. Urban and rural air temperatures are similar during early morning hours, but a heat island begins to develop mid-morning and intensifies during the late afternoon as the rural area cools more rapidly than the urban area. The maximum heat island occurs near sunset (4.3°C). The urban latent heat flux is substantially less than the rural during daytime, which contributes to warmer urban temperatures. The urban area stores significantly more heat during the day and releases it later in the day and at night, thereby maintaining a near-zero or positive sensible heat flux at all times which keeps the urban area warmer than the rural.

[12] There is little change in the atmospheric forcing in the ALB simulation compared to the CON simulation for this particular grid cell, and so the rural energy balance and air temperature are nearly unchanged in the two simulations (Figure 2). Increasing the roof albedo from 0.32 in the CON simulation to 0.90 in the ALB simulation reduces the summer (JJA) mean urban heat island by about 0.5°C for this particular grid cell. Urban net radiation decreases by about 200 $W\ m^{-2}$ at local noon. In response, daytime sensible and storage heat flux decrease. This cools daytime urban temperatures, but nighttime temperatures are only slightly cooler because there is still a substantial amount of heat released from urban surfaces at night.

[13] In the example shown in Figure 2, the main effect of an increase in roof albedo is to reduce urban daytime maximum temperature more than nighttime minimum temperature. This behavior is consistent from a global perspective as well. Averaged over all urban areas, the reduction in urban daily maximum temperature (−0.56°C) is about twice that of the reduction in daily minimum temperature (−0.26°C). This results in a decrease in the urban diurnal temperature range of −0.3°C.

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL042194.

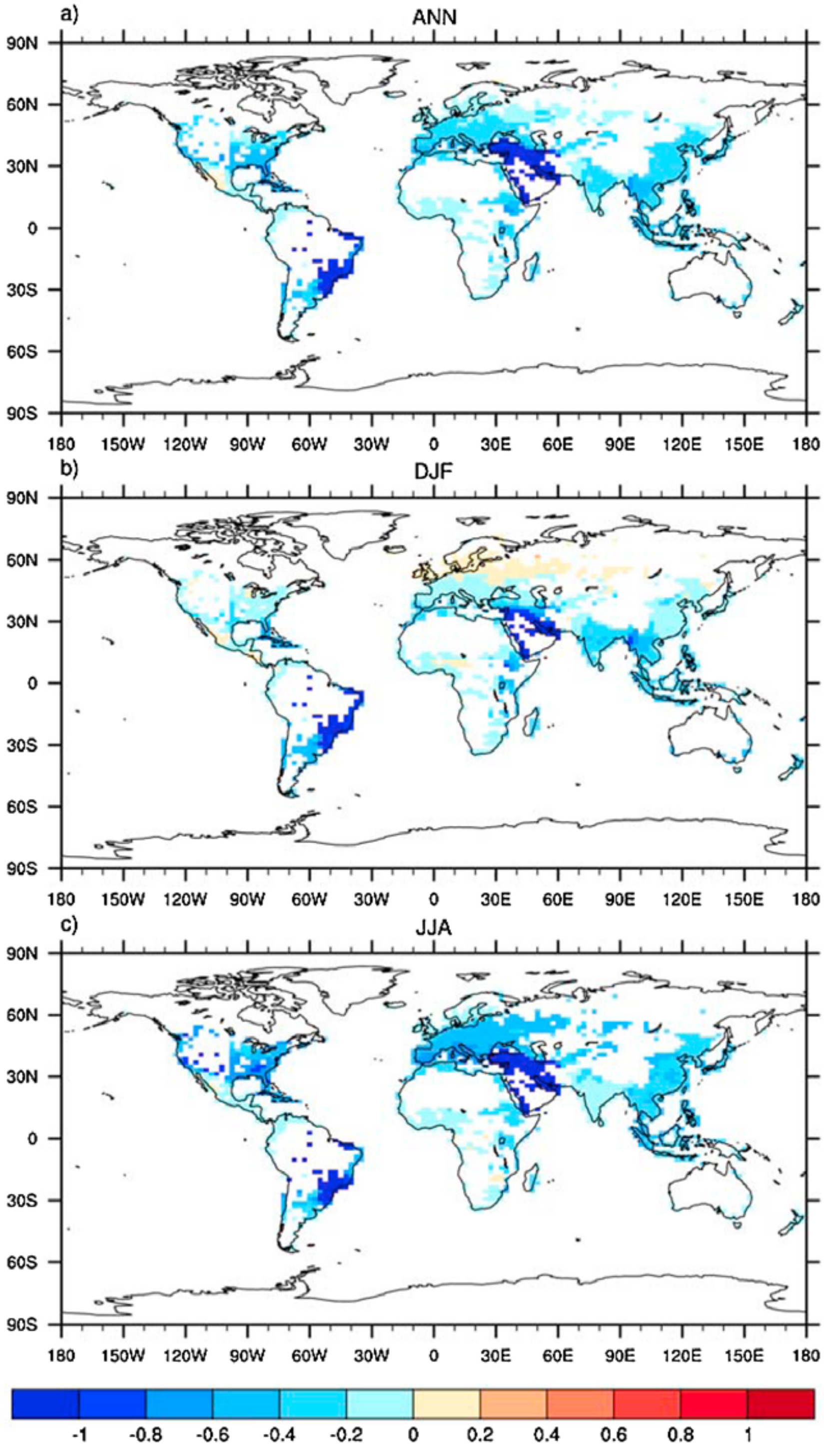

Figure 1. ALB minus CON simulations of urban minus rural air temperature for 1980–1999 climatology (°C) (a) annual (ANN), (b) December–February (DJF), (c) June–August (JJA). The urban temperature is the air temperature in the urban canopy layer. The rural temperature is the average 2-m air temperature of the "rural" surfaces (i.e., the vegetated and bare soil surfaces) in the grid cell. Land areas displayed in white are grid cells that have zero urban area in the model.

[14] There is large spatial variability in the change in heat island (Figure 1). Linear regression analysis identified the main causes of this variability. The change (ALB minus CON) in the annual mean heat island is strongly positively correlated with the change in the urban absorbed solar radiation (r = 0.70, $p \ll 0.01$). The change in absorbed solar radiation is a function of the magnitude of the incoming solar radiation and urban characteristics. For instance, more solar radiation is reflected in urban areas with larger roof fraction and a larger increase in roof albedo (lower albedo in the CON simulation). The Arabian Peninsula and Brazil are examples of regions where the urban

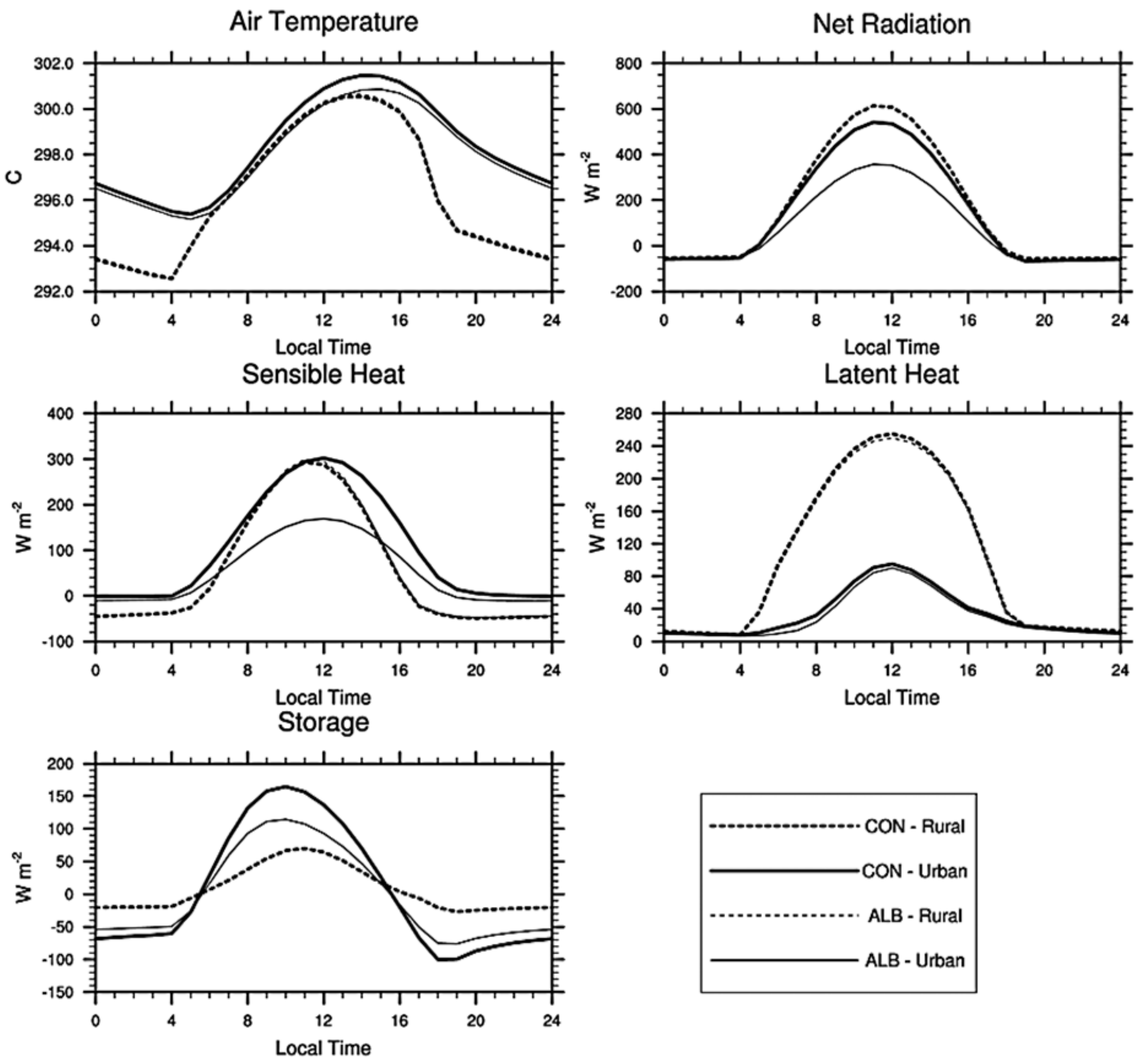

Figure 2. Summer (JJA) climatological (1980–1999) diurnal cycle of urban and rural air temperature and energy balance for a grid cell in the northeast U.S. (40.7°N, 287.5°E) for the ALB and CON simulations.

areas have relatively low roof albedo in the control simulation and large roof fraction.

[15] The role of roofs as a contributor to the storage and release of heat in the urban system is also a source of variability in the change in the heat island. The change in the heat island is positively correlated with roof thermal admittance [$\sqrt{\lambda_{roof} c_{roof}}$ where λ_{roof} is the thermal conductivity (W m^{-1} K^{-1}) and c_{roof} is the volumetric heat capacity (J m^{-3} K^{-1})] ($r = 0.39$, $p \ll 0.01$). Roofs are thin and large thermal admittance allows heat to be conducted more easily into the building interior such that daytime storage and nighttime release of heat within the roof is relatively small. Thus, the nighttime heat island remains about the same despite the reduction in solar absorption. Mexico and the Sahel are examples of regions with small changes in the heat island despite large decreases in urban absorbed solar radiation. The roof properties specified by the urban dataset in these regions are for materials with high thermal admittance such as metals with little or no insulation. Together, these two factors (changes in urban absorbed solar radiation and roof thermal admittance, in order of importance) explain 81% of the spatial variation in the change in annual mean heat island ($r^2 = 0.81$, $p \ll 0.01$ from multiple linear regression analysis).

[16] At northern latitudes in boreal winter, the increase in roof albedo is less efficient at reducing the heat island. In particular, the heat island is unchanged or even larger in the ALB simulation in northern Europe and Eurasia (Figure 1). In contrast, the boreal summer heat islands in these regions are reduced by 0.5°C or more. In large part this is due to low incoming solar radiation, which makes the increase in roof albedo less effective at reducing urban temperatures. The increase in roof albedo is also likely less effective because of the influence of snow, which has relatively high albedo. The model's representation of space heating also plays a role. At these latitudes the winter urban heat island is partially maintained by space heating that is necessary to keep the building interior temperature above a minimum comfort level. This is demonstrated in Figure 3a, which compares the heat island in the offline CON_O and CON_O_NHAC simulations. At latitudes north of 20°N, the inclu-

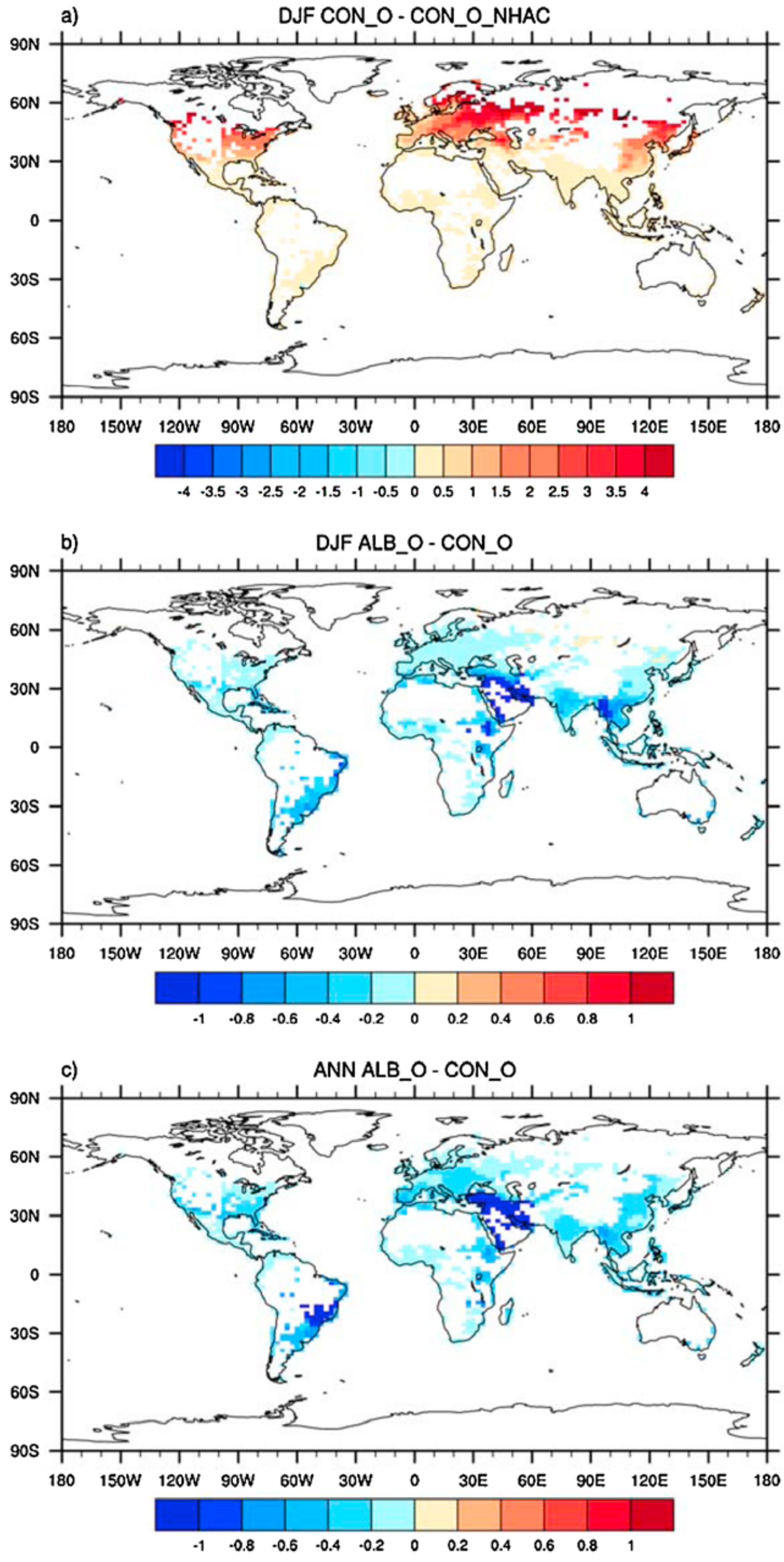

Figure 3. Differences in climatology (years 6–10) of urban minus rural air temperature (°C) for (a) DJF CON_O minus CON_O_NHAC, (b) DJF ALB_O minus CON_O, (c) ANN ALB_O minus CON_O.

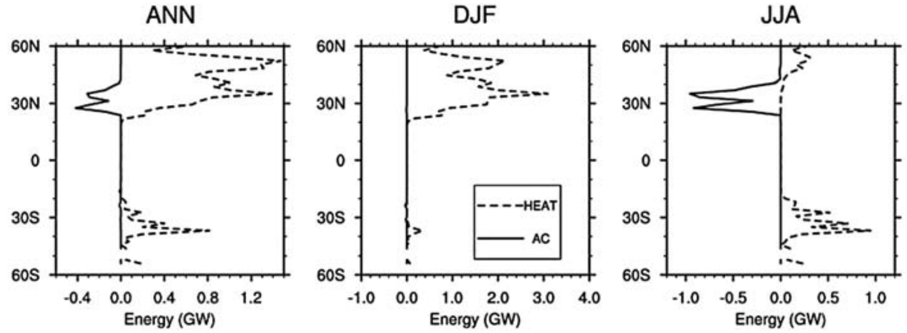

Figure 4. Zonal means of ALB minus CON simulations of urban space heating (HEAT) and air conditioning (AC) energy for 1980–1999 annual, DJF, and JJA climatology (gigawatts).

sion of space heating and associated waste heat significantly increases the heat island (Figure 3a). In the ALB simulation, the high roof albedo reduces heat conduction into the building interior, and space heating therefore increases to maintain the interior building temperature (Figure 4). Similar behavior can be seen in southern hemisphere winter south of 20°S, where the reduction in the heat island is generally smaller than in summer due to an increase in space heating.

[17] Some of the increase in the boreal winter heat island in northern Eurasia is also due to differences in atmospheric temperature between the two simulations because of internal variability in the atmospheric model. Even though there are no statistically significant changes in atmospheric temperature, the ALB simulation has temperatures that are 0.4–1.6°C colder than the CON temperatures in this region (not shown). This change in atmospheric temperature cools both rural and urban near-surface air temperatures. However, the rural temperature cools more than the urban temperature because the space heating increases in the urban area. This contributes to a slightly larger heat island in the ALB compared to the CON simulation. In comparison, the atmospheric temperatures are identical and the northern Eurasia heat island is nearly unchanged in the offline simulations ALB_O and CON_O (Figure 3b). Thus, differences in the coupled model simulations at high latitudes result from internal atmospheric model variability; this appears to be on the order of ±0.2°C. A comparison of Figure 3c (offline simulations with identical atmospheric forcing constrained by observations) with Figure 1a (coupled simulations) indicates that the results are not sensitive to biases in simulated climate, as the spatial patterns are quite similar.

[18] Air conditioning in the model is assumed to occur primarily in the U.S. and so there is a modest decrease in air conditioning flux from about 20–40°N due to the reduced solar absorption (Figure 4). The globally averaged annual air conditioning flux decreases from 0.09 TW in the CON simulation to 0.02 TW in the ALB simulation, while space heating flux increases from 5.61 TW to 6.30 TW. Thus, the sum of space heating and air conditioning flux increases by 0.62 TW (from 5.70 TW to 6.32 TW).

3. Conclusions

[19] These results suggest that increasing the albedo of roofs is an effective way of reducing the urban heat island. The degree to which the heat island decreases depends on the importance of roofs relative to the rest of the urban system (i.e., building walls and canyon floor) in generating the heat island. This approach to heat island mitigation is less effective in winter at higher latitudes. At these latitudes, any benefits gained from a reduction in the summertime heat island need to be considered in the context of increased heating costs in winter. Increasing the albedo of roofs is also less effective for thin roofs constructed with high thermal admittance materials because these roofs have low storage capacities. Globally, white roofs cause a net increase in HAC fluxes due to a larger increase in space heating than decrease in air conditioning flux. As air conditioning more thoroughly penetrates the global market, however, white roofs might be expected to play a larger role in reducing this flux.

[20] **Acknowledgments.** This research was supported by National Science Foundation grants ATM-0107404 and ATM-0413540, and the University of Kansas, Center for Research. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

Akbari, H., S. Menon, and A. Rosenfeld (2009), Global cooling: Increasing world-wide urban albedos to offset CO_2, *Clim. Change*, *94*, 275–286, doi:10.1007/s10584-008-9515-9.

Collins, W. D., et al. (2006), The Community Climate System Model version 3 (CCSM3), *J. Clim.*, *19*, 2122–2143, doi:10.1175/JCLI3761.1.

Dobson, J. E., E. A. Bright, P. R. Coleman, R. C. Durfee, and B. A. Worley (2000), LandScan: A global population database for estimating populations at risk, *Photogramm. Eng. Remote Sens.*, *66*, 849–857.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Neale, R. B., J. H. Richter, and M. Jochum (2008), The impact of convection on ENSO: From a delayed oscillator to a series of events, *J. Clim.*, *21*, 5904–5924, doi:10.1175/2008JCLI2244.1.

Oke, T. R. (1987), *Boundary Layer Climates*, 2nd ed., 435 pp., Routledge, London.

Oleson, K. W., G. B. Bonan, J. Feddema, M. Vertenstein, and C. S. B. Grimmond (2008a), An urban parameterization for a global climate model. 1. Formulation and evaluation for two cities, *J. Appl. Meteorol. Climatol.*, *47*, 1038–1060, doi:10.1175/2007JAMC1597.1.

Oleson, K. W., G. B. Bonan, J. Feddema, and M. Vertenstein (2008b), An urban parameterization for a global climate model. 2. Sensitivity to input parameters and the simulated urban heat island in offline simulations, *J. Appl. Meteorol. Climatol.*, *47*, 1061–1076, doi:10.1175/2007JAMC1598.1.

Oleson, K. W., et al. (2008c), Improvements to the Community Land Model and their impact on the hydrological cycle, *J. Geophys. Res.*, *113*, G01021, doi:10.1029/2007JG000563.

Qian, T., A. Dai, K. E. Trenberth, and K. W. Oleson (2006), Simulation of global land surface conditions from 1948 to 2004. Part I: Forcing data and evaluations, *J. Hydrometeorol.*, *7*, 953–975, doi:10.1175/JHM540.1.

Sailor, D. J. (1995), Simulated urban climate response to modifications in surface albedo and vegetative cover, *J. Appl. Meteorol.*, *34*, 1694–1704.

Synnefa, A., A. Dandou, M. Santamouris, and M. Tombrou (2008), On the use of cool materials as a heat island mitigation strategy, *J. Appl. Meteorol. Climatol.*, *47*, 2846–2856, doi:10.1175/2008JAMC1830.1.

Taha, H., St. Konopacki, and S. Gabersek (1999), Impacts of large-scale surface modifications on meteorological conditions and energy use: A 10-region modeling study, *Theor. Appl. Climatol.*, *62*, 175–185, doi:10.1007/s007040050082.

G. B. Bonan and K. W. Oleson, Climate and Global Dynamics Division, National Center for Atmospheric Research, PO Box 3000, Boulder, CO USA.

J. Feddema, Department of Geography, University of Kansas, 213 Lindley Hall, Lawrence, KS 66045, USA.