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LETTER

Investigating the climate impacts of urbanization and the potential for cool roofs to counter future climate change in Southern California

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Abstract

The climate warming effects of accelerated urbanization along with projected global climate change raise an urgent need for sustainable mitigation and adaptation strategies to cool urban climates. Our modeling results show that historical urbanization in the Los Angeles and San Diego metropolitan areas has increased daytime urban air temperature by 1.3 °C, in part due to a weakening of the onshore sea breeze circulation. We find that metropolis-wide adoption of cool roofs can meaningfully offset this daytime warming, reducing temperatures by 0.9 °C relative to a case without cool roofs. Residential cool roofs were responsible for 67% of the cooling. Nocturnal temperature increases of 3.1 °C from urbanization were larger than daytime warming, while nocturnal temperature reductions from cool roofs of 0.5 °C were weaker than corresponding daytime reductions. We further show that cool roof deployment could partially counter the local impacts of global climate change in the Los Angeles metropolitan area. Assuming a scenario in which there are dramatic decreases in greenhouse gas emissions in the 21st century (RCP2.6), mid- and end-of-century temperature increases from global change relative to current climate are similarly reduced by cool roofs from 1.4 °C to 0.6 °C. Assuming a scenario with continued emissions increases throughout the century (RCP8.5), mid-century warming is significantly reduced by cool roofs from 2.0 °C to 1.0 °C. The end-century warming, however, is significantly offset only in small localized areas containing mostly industrial/commercial buildings where cool roofs with the highest albedo are adopted. We conclude that metropolis-wide adoption of cool roofs can play an important role in mitigating the urban heat island effect, and offsetting near-term local warming from global climate change. Global-scale reductions in greenhouse gas emissions are the only way of avoiding long-term warming, however. We further suggest that both climate mitigation and adaptation can be pursued simultaneously using 'cool photovoltaics'.

Introduction

An important consequence of urbanization is the urban heat island (UHI), defined as a rise in temperatures over urban areas relative to surrounding rural areas (Tran *et al* 2006, Santamouris 2007). This well-documented effect is linked to degraded thermal comfort (Pantavou *et al* 2011, Lee *et al* 2012, Mishra and Ramgopal 2013, Taleghani *et al* 2016), increased cooling energy use (Hassid *et al* 2000, Fung *et al* 2006, Kolokotroni *et al* 2007, Hirano and Fujita 2012, Salamanca *et al* 2013), deterioration of air quality (Huizenga *et al* 2006, Sarrat *et al* 2006, Stathopoulou *et al* 2008, Nazaroff 2013), and heat-related morbidity and mortality (Patz *et al* 2005, Li and Bou-Zeid 2013, Mishra and Ramgopal 2013). The UHI effect is caused by land cover change and anthropogenic heat release as a result of urbanization, both of which alter the energy balance of the land surface (Oke 1982, Grimmond 2007). For example, reduced vegetation cover in

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cities can lead to decreased evaporative cooling. Surface albedo change through urbanization can either increase or decrease absorbed solar radiation, depending on the albedo of the natural surface that urbanization has replaced. Man-made materials used in urban areas store more of the Sun's energy during the day, compared to vegetation and soil, and release this stored energy at night, leading to nocturnal warming. Urbanization also affects the efficiency of convection over urban surfaces, which in turn alters energy exchange between the land surface and the atmospheric boundary layer and consequently surface and near-surface temperatures (Oke 1982, Arnfield 2003, Grimmond 2007, Zhao *et al* 2014). Finally, anthropogenic heat release contributes to temperature increases by introducing an additional energy source to the lower atmosphere.

Under the pressing challenges of accelerated urbanization and projected global-scale climate change, there is an urgent need for sustainable mitigation and adaptation strategies that can cool urban climates. Among the proposed strategies, solar reflective roofs (hereafter referred to as 'cool roofs') have gained broad acceptance as a promising approach to mitigate UHI effects (Doulos *et al* 2004, Akbari and Levinson 2008, Taha 2008a, 2008b, Millstein and Menon 2011, Santamouris *et al* 2011, Akbari and Matthews 2012, Stone *et al* 2012, Georgescu *et al* 2013, 2014, Taha 2013, Li and Bou-Zeid 2014, Li *et al* 2014, Santamouris 2014, Ban-Weiss *et al* 2015a, 2015b). Over the past decades, several studies have illustrated the potential efficacy of cool roofs to reduce indoor and outdoor temperatures (see reviews by Santamouris 2014 and Yang *et al* 2015), decrease cooling loads (Santamouris 2014), avoid heat-related mortality (Stone *et al* 2014), and lead to negative global radiative forcing with the potential of offsetting billions of tons of CO_2 emission (Akbari *et al* 2008, Akbari *et al* 2012). On the other hand, a recent review study showed that the effectiveness of cool roofs can depend on many city-specific factors including meteorological and geographical conditions and building characteristics (Yang *et al* 2015).

In this study, we first characterize the impacts of historical urbanization on the climate of the Los Angeles and San Diego metropolitan regions, the second and seventieth largest metropolitan areas in the United States (US Census Bureau 2016). This is carried out by comparing the simulated current climate of Southern California with a scenario that assumes the likely land cover of the region prior to widespread urbanization. As a widely discussed UHI mitigation strategy, we next compare the cooling effects of three phases of cool roof implementation over Industrial/Commercial, Residential, and both Residential and industrial/commercial areas. An important question is whether, and to what extent, the cooling effects of implemented cool roofs can potentially offset future local warming associated with global climate change. To illustrate the relative effectiveness of cool roofs, we compare cool roof-induced cooling with projected mid- and end-of-century surface air warming associated with large-scale global climate change over the Los Angeles metropolitan area.

This is the first study to (a) quantify the impact of historical urbanization on the climate of Southern California metropolitan areas and (b) assess the effectiveness of cool roofs in the context of both urbanization and global climate change. We further discuss the prospect of highly efficient and solar reflective photovoltaics ('cool PV') to be used for both climate change mitigation and adaptation. This study relies on an advanced regional climate modeling framework that is enhanced with urban parameterizations and current urban land cover/characteristics datasets. This study is also unique in the way that it takes advantage of real-time and high-resolution remotely sensed information, not only to characterize the modeled urban surfaces in their current state, but also to quantify the physical characteristics of current natural lands in and around the Los Angeles and San Diego basins as a proxy for the natural land cover that existed throughout the basin prior to widespread urbanization.

Materials and methods

Climate model

We use a satellite-supported version of the Weather Research and Forecasting model (WRF) (Skamarock and Klemp 2008, Skamarock *et al* 2008) to simulate the climate of an area of 72 000 km^2, centered over Southern California (figure 1). WRF is a state-of-the-art, fully compressible, non-hydrostatic, mesoscale numerical weather prediction model. In the current study we extend the capabilities of WRF by incorporating satellite-based real-time high-resolution surface physical characteristics including albedo, green vegetation fraction (GVF), and LAI. WRF is coupled with a single-layer urban canopy model (UCM) that treats urban physical processes (Kusaka *et al* 2001, Kusaka and Kimura 2004). The UCM calculates the surface energy balance for urban surfaces, accounting for the three-dimensional nature of urban surfaces as well as shadowing, reflections, trapping of radiation, and wind profiles inside a street canyon (Chen *et al* 2011). A detailed description of the WRF-UCM initial and boundary conditions as well as physics parameterizations is included in the supplementary information.

Satellite-based land surface characteristics

Albedo plays an important role in the surface energy dynamics by defining the amount of solar radiation reflected from the surface (Dickinson 1983, Dobos 2003, Cedilnik *et al* 2012). GVF and LAI are also key parameters that control the partitioning of evaporative flux into bare-soil evaporation and vegetation evapotranspiration (Chen and Dudhia 2001). The WRF has built-in options to define albedo relying

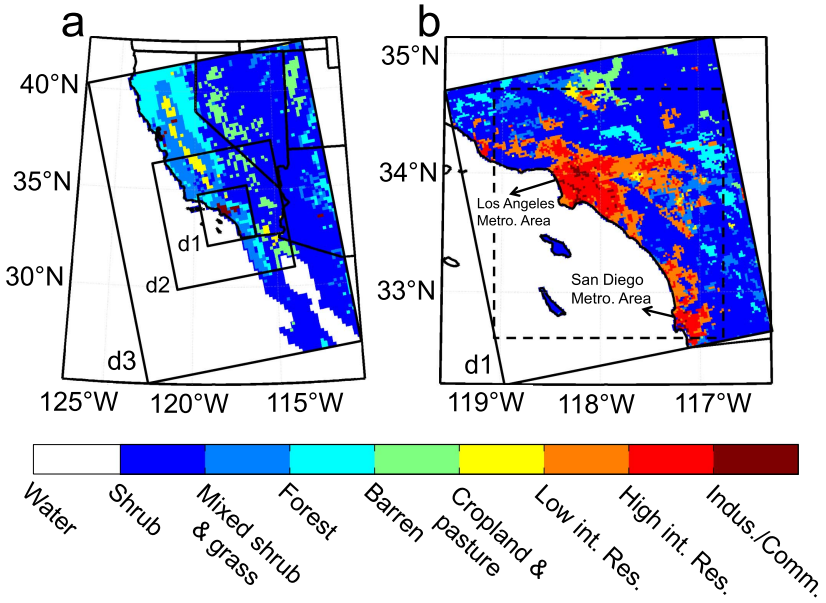

Figure 1. Maps showing (a) geographical representation of the three nested WRF-UCM domains with 18, 6, and 2 km resolution for d3, d2, and d1, respectively, and (b) dominant land cover types per grid cell for the innermost domain d1. The dashed line represents the area for which the results are illustrated throughout this study.

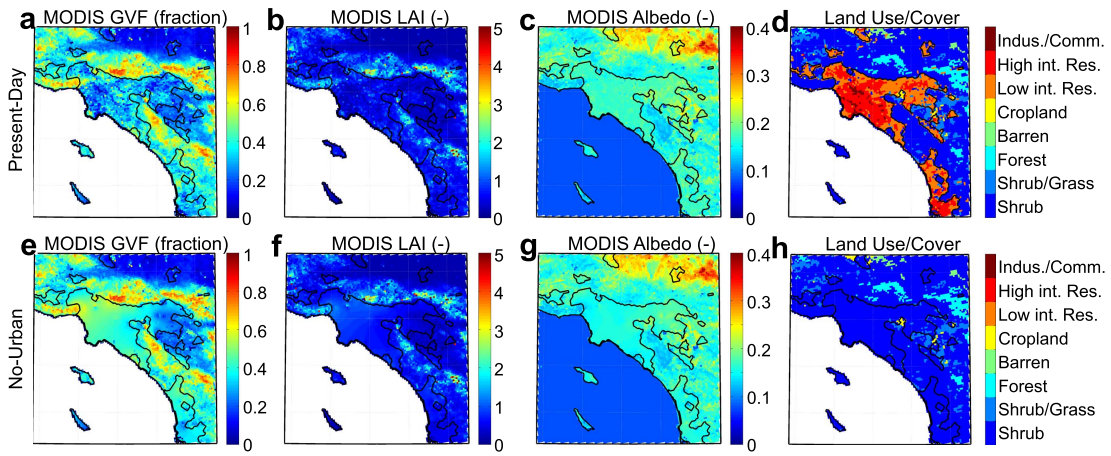

Figure 2. GVF, LAI, albedo, and land use/cover maps for present-day (top row) and no-urban (bottom row) based on real-time MODIS data. For no-urban, the GVF, LAI, and albedo values over urban surfaces are updated using information from surrounding shrub areas and the inverse distance weighting approach. Results are presented for the month of July.

either on land cover dependent tabulated values or five-year mean (1985–1990) climatological data from the advanced very high resolution radiometer (AVHRR) (Gutman and Ignatov 1998, Csiszar and Gutman 1999) with spatial resolution of 0.144°. For GVF, the model provides two options of using mean climatological data from AVHRR (1985–1990) or moderate-resolution imaging spectroradiometer (MODIS) (2001–2010). Furthermore, WRF by default relies on land cover dependent tabulated values to estimate LAI. In recent versions, an option to utilize MODIS-based climatological (mean over 2001–2010) LAI is also included. Despite the advantages of adding MODIS-based data, the built-in climatological representation of critical land surface characteristics (e.g. albedo, GVF, and LAI) does not reflect the reality of the land surface state for a given year. To overcome this shortcoming, in the current study we improve the representation of urban surface physical characteristics in WRF by incorporating satellite-based real-time high-resolution albedo, GVF, and LAI (figures 2(a)–(c)). We use MODIS observations to replace default climatological maps and tabulated values. MODIS data are obtained from the US Geological Survey (USGS) National Center for Earth Resource Observations and Science (EROS) website at http://earthexplorer.usgs.gov. We generate domain-specific real-time monthly maps of albedo, GVF, and leaf area index (LAI) based on MODIS reflectance (MCD43A4), vegetation indices (MOD13A3), and fraction of

photosynthetically active radiation (MCD15A3) products, respectively. These maps are re-gridded to the WRF-UCM spatial resolution (2 km) and coordinate system.

A perhaps even more important limitation with the standard version of WRF-UCM is that the pervious portions of urban grid-cells are assigned with unvarying and predefined GVF and albedo values (Vahmani and Ban-Weiss 2016a). Thus, any heterogeneity in vegetation within urban areas cannot be resolved. In this study, we remove this simplifying assumption and use high-resolution, real-time remote sensing data to replace these constant predefined values. A detailed description of the satellite-supported WRF-UCM and the implemented remotely sensed land surface characteristics is presented in a previous study by the authors (Vahmani and Ban-Weiss 2016a).

Model validation

The authors have published an extensive validation of the utilized satellite-supported WRF-UCM modeling framework (Vahmani and Ban-Weiss 2016a). The WRF-UCM performance is validated using satellite-based land surface temperatures as well as ground observations of near-surface air temperature and evapotranspiration. It is reported (Vahmani and Ban-Weiss 2016a) that the predictive capabilities of the WRF-UCM is improved over the Los Angeles metropolitan region after incorporation of realistic satellite-based representation of aforementioned land surface characteristics. For example, the root-mean-square difference between simulated and observed nocturnal surface air temperatures is reduced by about 50%.

Model simulations

To investigate the UHI and the climate impacts of cool roof adoption, we carry out a series of ensemble-based simulations representing present-day (control), no-urban, and cool-roof scenarios. For cool-roof, cool roofs are implemented over all the buildings within the study domain. We further conduct simulations that limit cool roof adoption to only residential (cool-roof-R) and industrial/commercial (cool-roof-I/C) buildings to assess the relative importance of each building type in reducing urban temperatures. All simulations are carried out using three (two-way) nested grids, centered over Southern California with 30 vertical layers and horizontal resolutions of 18 km, 6 km and 2 km, respectively (figure 1). The simulations are carried out from 29 June, 0700UTC (12:00 am local standard time) to 31 July, 0700UTC (12:00 am local standard time) for 2010, 2011, and 2012, including a spin-up of 24 h. We focus on urban climate during the month of July, when the 17 million residents of the Los Angeles and San Diego metropolitan areas (US Census Bureau 2016) are exposed to high heat-related stress levels (Akbari *et al* 2001). All simulations utilize the enhanced satellite-supported WRF that allows for real-time MODIS-based representation of GVF, LAI, and albedo (see Vahmani and Ban-Weiss (2016a) for details). The present-day and cool-roof simulations, which include urban surfaces, also incorporate urban irrigation (see supplemental information for details). For realistic representation of cool roof adoption over residential versus non-residential areas, the urban type (i.e. low intensity residential, high intensity residential, or industrial/commercial) and urban fraction of each grid-cell is determined based on the very high-resolution (30 m) National Land Cover Database (NLCD) (Fry *et al* 2011) and NLCD impervious surface data (Wickham *et al* 2013), respectively. The urban classification (residential versus non-residential) is determined based on the dominant urban class in each model grid-cell.

To quantify the significance of simulated results, we use the two-sided Student's t test to statistically compare urbanization and cool roof induced changes with the natural fluctuations associated with the climate system and the model internal variability. We only include differences that are statistically significant at the 95% confidence interval, relative to the daily variations in the multiyear ensemble members for each grid-cell. The areas with non-significant signals are excluded from the maps presented in this study.

Calculation of UHI

The UHI is typically characterized by comparing temperatures within urban areas to surrounding rural areas. Estimating the UHI in the Los Angeles metropolitan area is particularly difficult due to the lack of surrounding rural areas (Roth *et al* 1989, Witiw and LaDochy 2008, Vahmani and Ban-Weiss 2016a) as the metropolitan area is immediately surrounded by mountain ranges and the Pacific Ocean. To quantify the UHI we designed a hypothetical land surface representation (no-urban) that replaces all urban surfaces with shrubs, the native vegetation to the region. By comparing the 'no-urban' with 'present-day' scenario, we evaluate the UHI as urbanization-induced temperature changes over the areas that are presently urban.

For an accurate representation of no-urban land surface characteristics, we utilize remotely sensed albedo, GVF, and LAI over grid-cells covered with shrubs within and surrounding the metropolitan area. We made use of the inverse distance weighting approach (Shepard 1968) (with power parameter of 2) to calculate interpolated albedo, GVF, and LAI values for grid-cells that are presently urban and are converted to shrub lands in the No-Urban scenario (figure 2). The present-day shrub areas are cautiously selected to avoid including information from areas far from the metropolitan region or with vastly different characteristics such as high elevation (figure 3).

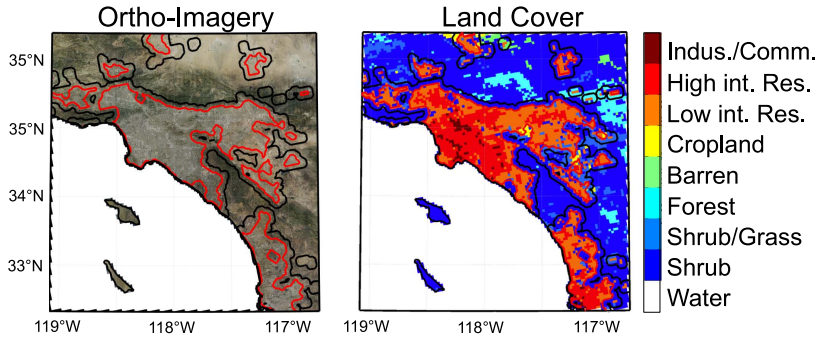

Figure 3. Ortho-imagery and land use/cover maps. The red lines illustrate the extent of the urban regions of the Los Angeles and San Diego metropolitan areas. The areas between the red and black lines show grid-cells currently covered with shrubs within and surrounding the metropolitan area that are used to estimate albedo, GVF, and LAI of shrub lands in no-urban.

Cool roof representation in the model

To quantify the potential for cool roofs to mitigate the UHI in the Los Angeles and San Diego metropolitan areas, we repeat the present-day simulations but increase building roof albedos to those of cool roofs. Based on cool roofs that are currently commercially available, we assume albedos of 0.85 and 0.40 as the highest achievable 'aged' (i.e. after accounting for pollution deposition onto the rooftop) values for industrial/commercial and residential roofs, respectively. (As of November 2016, the Rated Products Directory of the Cool Roof Rating Council (CRRC 2016) lists roofing products with aged albedos as high as 0.87 for field applied elastomeric coatings designed for low slope roofs, and 0.37 for non-white cool shingles for residential pitched roofs.) While residential cool roofs with higher albedos exist when using white materials, we chose 0.40 as a value consistent with darker colored roofs that are often the aesthetic preference of home owners. We emphasize that the selected albedo for residential buildings is also consistent with the 'effective albedo' of high efficiency solar photovoltaics (PV) that are currently in development. ('Effective albedo' is defined as PV reflectance + PV conversion efficiency.) Future technical improvements in PV design and configuration are expected to increase PV reflectivity up to values of 10% using coatings that selectively reflect wavelengths below the semiconductor material's bandgap (Nemet 2009, Protogeropoulos and Zachariou 2010). The solar conversion efficiency of PV systems is also anticipated to reach up to 0.30, meaning the effective albedo of solar PV panels would reach up to 0.40 (Nemet 2009 and Taha 2013). Thus, the residential cool roof albedos chosen are consistent with a scenario involving adoption of high efficiency PV. A few previous studies have investigated the climatic impacts of widespread implementation of solar PV's at regional scale (Millstein and Menon 2011, Taha 2013, Salamanca *et al* 2016).

Future warming projections

We use a hybrid downscaling technique, reported by Walton *et al* (2015), to downscale mid-century (2041–60) and end-century (2081–2100) temperature changes, relative to a baseline period (1981–2000). The results are presented for two representative concentration pathways (RCPs) (Moss *et al* 2008, Meinshausen *et al* 2011, Taylor *et al* 2012). One (RCP2.6) corresponds to a dramatic (and probably unrealistic) slowdown in greenhouse gas emissions over the next few decades. The other (RCP8.5) is associated with continued emissions increases throughout the century. The land use/cover remains the same as the baseline for both pathways. Projections from all global climate models from Coupled Model Intercomparison Project Phase 5 (CMIP5) are included in this analysis. The projected warming signals, averaged over the month of July, are compared with our simulated climate impacts of cool roofs over the Los Angeles metropolitan area at a common resolution of 2 km. A detailed description of the warming projections can be found in Sun *et al* (2015).

Results

Impact of urbanization in Southern California

Urbanization in Southern California (including both the Los Angeles and San Diego metropolitan areas) is simulated to increase the daytime (2 pm) near-surface (2 m) air temperature (hereafter referred to as air temperature) by 1.3 °C, averaged over urban parts of the region during the month of July (figure 4(a)). More significant warming of 3.1 °C is evident at night (10 pm) (figure 4(b)). Similarly, urbanization causes a significant increase in nocturnal land surface temperature (hereafter referred to as surface temperature) of 6.1 °C (figure 4(d)). Daytime surface temperature, however, undergoes a substantial cooling of 7.7 °C, induced by urbanization (figure 4(c)). The nocturnal warming of air and surface temperatures are associated with the high heat capacity of man-made materials such as concrete, which enables urban surfaces to store energy during the day and release it at night. Furthermore, a recent study (Vahmani and Ban-Weiss 2016b) reported that increased irrigation can potentially lead

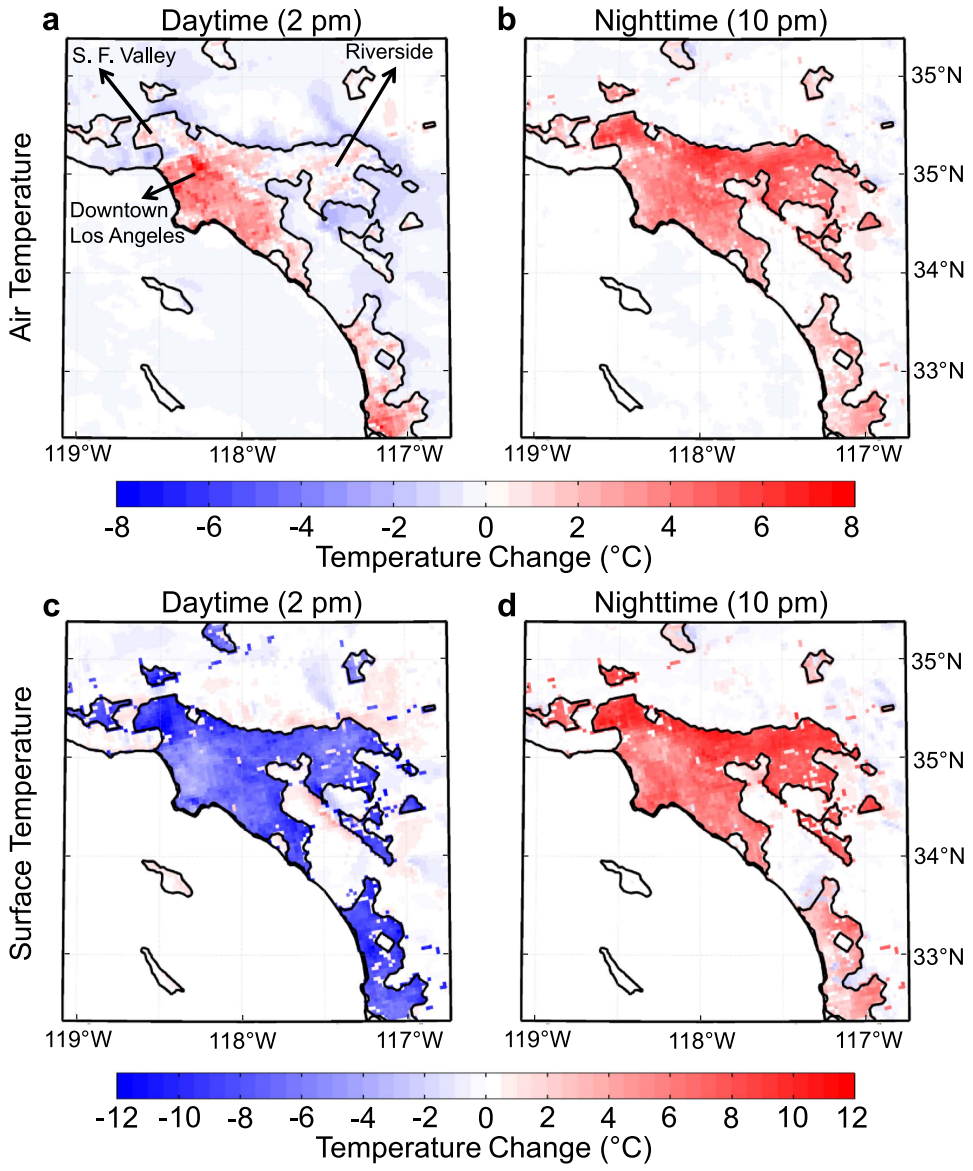

Figure 4. Simulated two-meter air (a, b) and surface temperature (c, d) differences induced by the urban heat island (present-day minus no-urban). Values represent mean temperature changes over July 2010, 2011, and 2012 at 2 pm (a, c) and 10 pm (b, d). The black lines illustrate the extent of the urban regions of the Los Angeles and San Diego metropolitan areas. Downtown Los Angeles, Riverside, and the San Fernando Valley (S. F. Valley) are labeled in (a). Only changes that are statistically distinguishable from zero at 95% confidence interval are shown.

to warming during the night as increased soil moisture alters the soil thermal properties to favor increased nocturnal upward ground heat fluxes. The daytime surface temperature cooling induced by urbanization can be explained by the addition of urban surfaces with high heat capacity, which reduces diurnal variability in surface temperatures, along with the evaporative cooling effects of urban irrigation.

Despite the cooling of the surface (figure 4(c)), and the urban irrigation induced shift in the partitioning of surface energy toward higher latent heat flux and lower sensible heat flux (supplementary figure S1), implementing the present-day urban surfaces leads to a significant warming of daytime air temperature (figure 4(a)). Our analysis shows that the aforementioned surface cooling and urban irrigation effects are overwhelmed by the atmospheric warming response that is induced partially by a weakening of the daytime onshore sea breeze circulation, which cools the region in the afternoon (Vahmani and Ban-Weiss 2016a). Urbanization results in substantially increased surface roughness lengths (supplementary figure S2) and consequently increased surface friction that slows down the advection of cooler maritime air over land and removal of warm air out of the basin (figure 5). The average daytime (2 pm) wind speed over the urban areas is reduced by 1.9 m s^{-1} over the month of July due to urbanization. This finding is important as it was previously thought that 'rougher' urban surfaces, relative to rural lands, have a cooling effect via enhanced convection efficiency (Oke 1982, Arnfield 2003, Zhao *et al* 2014). Our analysis shows that the opposite

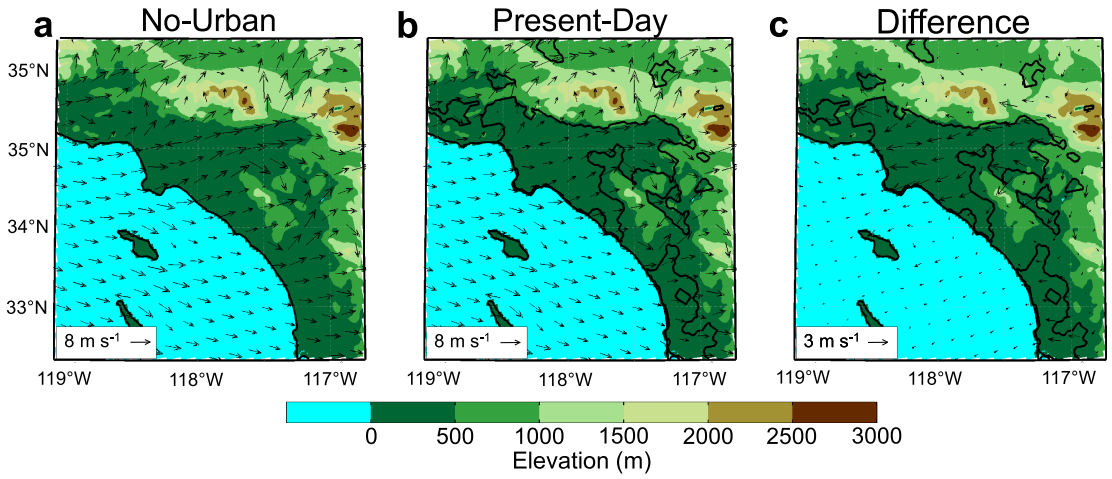

Figure 5. Simulated 10 m wind vectors over elevation map. The simulated 10 m wind vectors for (a) no-urban, (b) present-day, and (c) the difference (present-day—no-urban). The values represent wind vectors averaged over July 2010, 2011, and 2012 at 2 pm. The black lines illustrate the extent of urban areas. The mean wind speed at 2 pm over the urban areas is reduced by 1.9 m s^{-1} due to urbanization.

occurs in a coastal city that benefits from a cooling sea breeze; buildings increase surface friction and consequently impair the cooling onshore sea breeze circulation. The spatial variation in daytime air temperature warming (figure 4(a)) further indicates that urbanization has a stronger effect on the western portion of the Los Angeles basin that receives directly maritime air due to the sea breeze compared to the inland eastern basin (e.g. Riverside) or regions blocked by the mountains (e.g. San Fernando Valley). The mean temperature changes induced by urbanization for various regions in Southern California are presented in the supplementary information (table S1).

Our results also show that urbanization in Southern California metropolitan areas have significantly increased nighttime boundary layer heights and reduced nocturnal cloudiness near the ground surface layer (supplementary figure S3). These results support the findings of an observational study (Williams *et al* 2015) in coastal Southern California that reported that urbanization can induce nocturnal warming and increase the near surface dew point depression, the altitude of condensation, and cloud base height, consequently decreasing fog frequency.

Effectiveness of cool roofs versus urbanization impacts

Cool roof adoption for all building types (cool-roof) leads to a reduction of daytime air temperature by 0.9 °C, averaged over the metropolitan areas in Southern California during the month of July (figure 6(a)). Our analysis shows that cool roof adoption on residential buildings contributes to a significant portion (67% or 0.6 °C) of the cooling signal over the metropolitan area (figure 6(b)). The local cooling effects of industrial/commercial cool roofs are higher in magnitude, due to their higher roof albedos compared to residential cool roofs, and typically higher urban fractions compared to residential areas. However, this cooling response is confined to relatively small regions (figure 6(c)). Our results suggest that cool roofs on residential buildings would contribute more to city-wide cooling than industrial/commercial buildings. This is significant since areas such as the San Fernando Valley and Riverside, which are mostly comprised of residential homes and contain fewer industrial/commercial buildings (relative to downtown Los Angeles), have the highest baseline temperatures in the Los Angeles metropolitan area (supplementary figure S4). These elevated baseline temperatures are due to minimal cooling impacts of the sea breeze, which is blocked by the Santa Monica mountain range southwest of the San Fernando Valley, and impaired by the large distance between the Pacific Ocean and Riverside. It is noteworthy that our results corroborate the findings of a previous study (Taha 1997), one of the first to report on the potential of high-albedo materials as an effective measure to cool urban climates at regional scale. The mentioned study reported local cooling signals of up to 2 °C and 4.5 °C as a result of urban surface albedo increases of 0.15 and 0.30, respectively, on a late-August day in the Los Angeles metropolitan area.

Our results show that citywide adoption of cool roofs could be a viable way to meaningfully offset the daytime UHI effect in Southern California metropolitan areas by reducing the urbanization induced warming of 1.3 °C (figure 4(a)) by 0.9 °C (figure 6(a)). During nighttime, however, the mean air temperature reductions induced by cool roofs are smaller than daytime reductions. The mean nocturnal cooling from cool roof implementation over both residential and industrial/commercial, only residential, and only industrial/commercial buildings are 0.5 °C, 0.4 °C, and 0.1 °C, respectively (supplementary figure S5). The nocturnal cooling impacts of cool roofs are

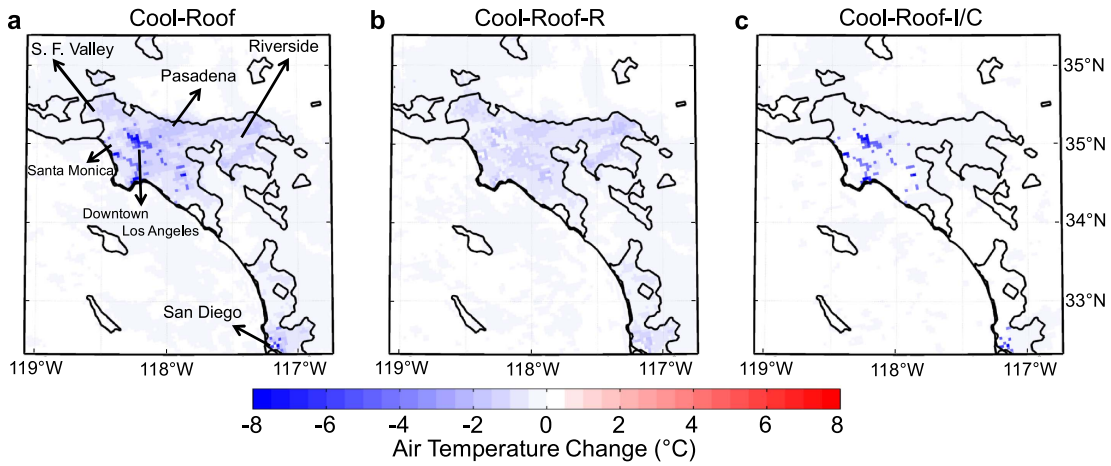

Figure 6. Simulated air temperature differences. Simulated air temperature changes induced by (a) cool roofs on residential and industrial/commercial buildings (cool-roof), (b) cool roofs on residential homes (cool-roof-R), and (c) cool roofs adopted on industrial/commerical buildings (cool-roof-I/C), relative to present-day. Values represent average temperature changes over July 2010, 2011, and 2012 at 2 pm. The black lines illustrate the extent of the urban regions of the Los Angeles and San Diego metropolitan areas. Downtown Los Angeles, Riverside, and San Fernando Valley (S. F. Valley) are labeled in (a). Only changes that are statistically distinguishable from zero at 95% confidence interval are shown.

significant since UHI induced high nocturnal temperatures reduce residents' ability to recover from hot daytimes, and cool down before the next day's exposure, increasing risk to public health (CAT (California Climate Action Team) 2013, Kalkstein *et al* 2013). This important effect of cool roofs on the nighttime climate of Southern California metropolitan areas is associated with reduced daytime heat storage in urban surfaces and consequently reduced release of stored heat during night.

The mean temperature changes induced by cool roofs for various regions in Southern California are presented in the supplementary information (table S1). Note that temperature reductions in inland cities are due to the climate impacts of cool roofs within the city, and also include additional contributions from cool roofs in upwind locations.

Effectiveness of cool roofs for countering local impacts of future climate change

To gain further insight into the mitigation and adaptation potential of cool roofs, we compare the diurnal mean temperature change induced by cool roofs versus the projected future near-surface air temperature increases over the Los Angeles metropolitan area for the month of July under global climate change. Mid- and end-of-century projected warming are considered for two greenhouse gas forcing scenarios. One (RCP2.6) corresponds to a dramatic slowdown in greenhouse gas emissions over the next decades while the other (RCP8.5) is associated with continued emissions increases throughout the century. The spatial distributions of projected mid- and end-of-century warming for the two scenarios are presented in the supplementary information (figure S6).

Our analysis of the residual warming attributed to climate change after cool roof implementation shows that cool roofs substantially reduce mid- and end-of-century diurnal average warming (relative to current climate) under RCP2.6 (from 1.4 °C to 0.6 °C, averaged over the urban portions of the region for Julys) (figures 7(a) and (c)). Under the RCP8.5 scenario, mid-century warming is also significantly offset by cool roofs (from 2.0 °C to 1.0 °C) (figure 7(b)). The end-century warming (relative to current climate) under the business as usual (RCP8.5) scenario, however, remains large (2.5 °C), even after cool roof implementation (figure 7(d)). This highlights the fact that cool roofs can only provide a meaningful reduction in urban temperatures over the coming few decades, and the necessity for global-scale greenhouse gas emission reductions for longer term regional climate stability. However, the implementation of industrial/commercial (see figure 1(b)) cool roofs show the capacity to locally counter warming signals under RCP8.5 through the end of century (see figure 7(d)). The local residual warming is negligible over the industrial/commercial areas, where the cool roofs with highest albedo are adopted; the increase in grid-cell level albedo in these areas is up to 0.29 (supplementary figure S7).

Discussion and conclusions

This study suggests that city-wide adoption of cool roofs, with currently available technologies, on both residential and industrial/commercial buildings can play an important role in mitigating the UHI effect, and offsetting near-term local warming from global climate change. Given the large role of residential cool roofs in reducing urban temperatures, we suggest

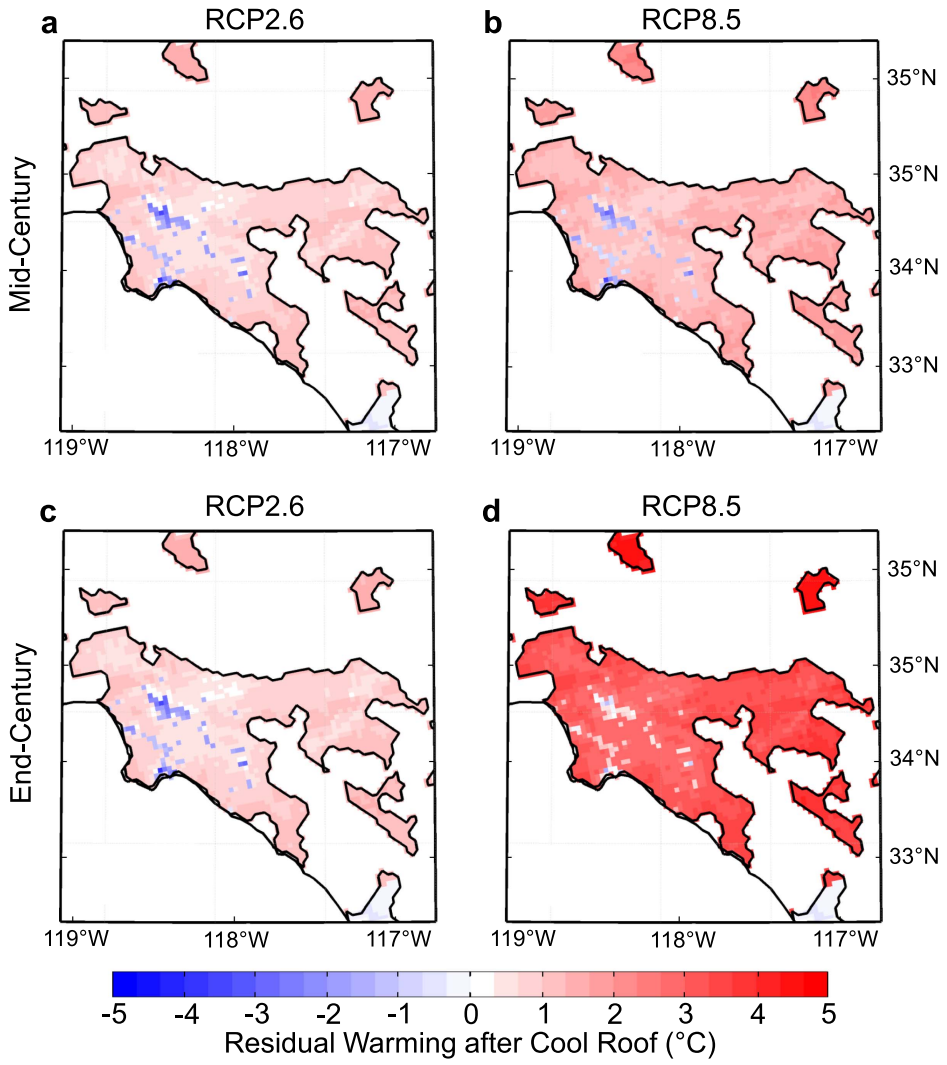

Figure 7. Simulated residual temperature change. Projected residual air temperature change from global climate change relative to current climate after cool roof adoption over industrial/commercial and residential areas for (a) mid-century (2041–60) under RCP2.6, (b) mid-century under RCP8.5, (c) end-century (2081–2100) under RCP2.6, and (d) end-century under RCP8.5. Values represent diurnal average temperature changes over the month of July. The results are only presented for urban areas (within black outlines). Only changes that are statistically distinguishable from zero at 95% confidence interval are shown.

future efforts to increase the albedo of residential cool roofs while maintaining desirable aesthetics and minimizing any cost differentials relative to standard roofs.

While we have shown that solar reflective cool roofs can counter near-term climate change, we have also made the point that longer term regional (and global) climate stability necessitates large-scale reductions in greenhouse gas emissions. Given that rooftops can house PV that produce carbon-free energy, use of rooftops for climate change mitigation (i.e. PV) versus adaptation (i.e. cool roofs) may seem at odds. We suggest, however, that both could be adopted simultaneously on residential roofs, especially with future technology development that maximizes solar conversion efficiency in the photoactive portion of the solar spectrum while reflecting wavelengths not used for electricity conversion. In this way, electricity production and air temperature reductions could be maximized by 'cool PV', allowing for both climate mitigation and adaptation to be pursued simultaneously.

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