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Summer-time climate impacts of projected megapolitan expansion in Arizona

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Efforts characterizing the changing climate of southwestern North America by focusing exclusively on the impacts of increasing levels of long-lived greenhouse gases omit fundamental elements with similar order-of-magnitude impacts as those owing to large-scale climate change[1,2]. Using a suite of ensemble-based, multiyear simulations, here we show the intensification of observationally based urban-induced phenomena and demonstrate that the direct summer-time climate effects of the most rapidly expanding megapolitan region in the USA—Arizona's Sun Corridor—are considerable. Although urban-induced warming approaches 4 °C locally for the maximum expansion scenario, impacts depend on the particular trajectory of development. Cool-roof implementation reduces simulated warming by about 50%, yet decreases in summer-time evapotranspiration remain at least as large as those from urban expansion without this mode of adaptation. The contribution of urban-induced warming relative to mid- and end-of-century climate change illustrates strong dependence on built environment expansion scenarios and emissions pathways. Our results highlight the direct climate impacts that result from newly emerging megapolitan regions and their significance for overcoming present challenges concerning sustainable development[3,4].

Direct effects of urbanization-induced land-use and land-cover change (LULCC) are an important driver of local to global change, with considerable implications for air quality, climate and natural resource sustainability[5–7]. Rapid population growth (Nevada: 66.3%, 35.1% and Arizona: 40.0%, 24.6% recorded the fastest national population growth rates between 1990–2000 and 2000–2010, respectively; the two states are the only ones in the USA to maintain a decadal population growth rate exceeding 20% since 1950; ref. 8) and associated urbanization-induced landscape modification[9] place the American southwest in a particularly vulnerable situation as mounting concerns related to large-scale anthropogenic climate change are layered on top of water-resource sustainability constraints resulting from rising demand[7]. An important question is whether, and to what extent, direct climatic impacts associated with rapidly urbanizing megapolitan regions in the US southwest are as important as those resulting from large-scale global climate change.

Located in the American southwest, the states of the Colorado River Basin are expected to add 23 million new residents between 2000 and 2030, with Arizona's burgeoning population accounting for roughly a quarter of projected growth, facilitating a top ten national ranking as one of the most populous states in the USA (ref. 10). The emergence of the Sun Corridor (megapolitan region stretching from the Arizona–Mexico border to northern Arizona; see Supplementary Information) as one of the largest megapolitan areas in the US (ref. 11), underscores the importance of well-timed and managed growth. Phoenix, Arizona, the largest city in the Colorado River Basin and at the heart of the emerging Sun Corridor, finds itself at a crossroads, in dire need of science-based policy decisions ensuring sustainable growth with minimal consequences for the natural environment[12]. Arizona's projected population increase is likely to encourage further landscape modification in future decades (2050 state estimates range between 8 and 16 million people[13]). Such drastic conversion to engineered structures has had and is expected to continue having significant impacts on local to regional scale climate (for example, by exacerbating an already significant urban heat island). For example, Fig. 1a shows the historically observed summer-time (June–August, JJA) average temperature and diurnal range (maximum minus minimum temperature) at Phoenix' Sky Harbor International Airport. Also illustrated are trends for both the average temperature and diurnal range, obtained with the linear regression method using a least squares fitting technique. The diurnal range progressively decreases with time, a manifestation of relentless urbanization driving the increase in urban-heat-island magnitude and rise in overall mean temperature, a feature not evident at a nearby non-urbanizing rural station (Fig. 1b). Evaluation of LULCC resulting from expansion of the built environment is necessary to address policy-relevant

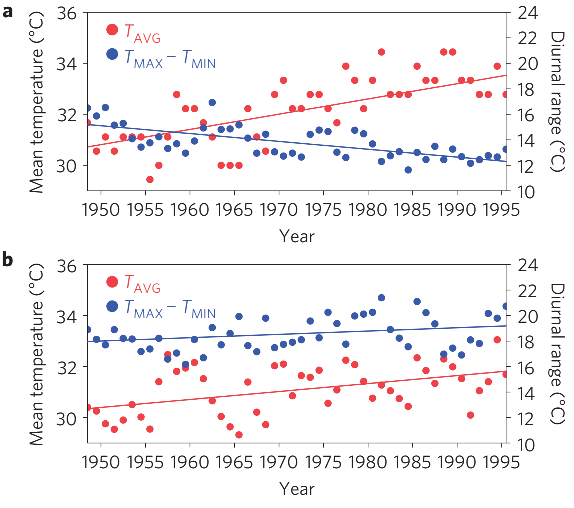

Figure 1 | Observed time series of the mean summer-time temperature and diurnal temperature range at an urbanizing and non-urbanizing station. Observed time series of the mean summer-time temperature (T_{AVG}) and diurnal temperature range ($T_{MAX} - T_{MIN}$) at **a**, Phoenix Sky Harbor International Airport, Arizona and **b**, Sacaton, Arizona. Straight lines represent trend of time series using a linear least squares fitting technique.

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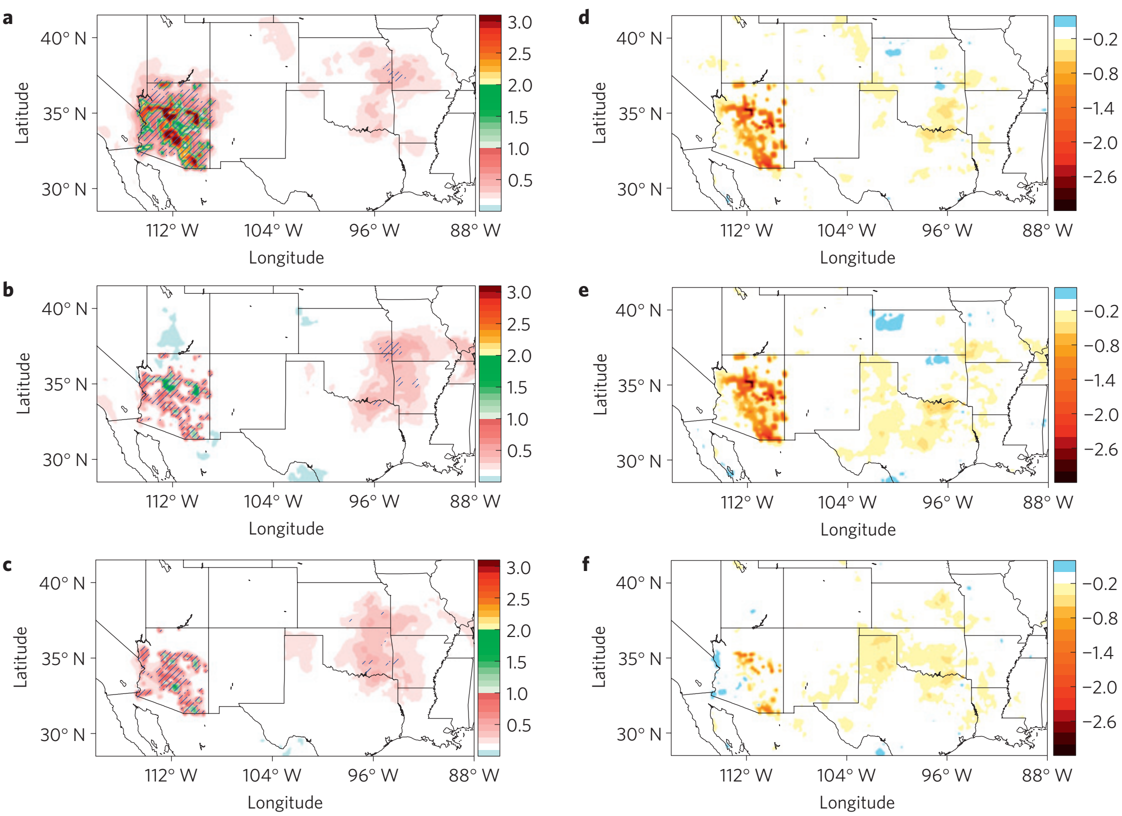

Figure 2 | Simulated summer-time two-metre air temperature and evapotranspiration differences. Simulated JJA two-metre air temperature difference (colour scale, °C) between **a**, SUNCORR_Hi and control; **b**, SUNCORR_Ad and control and **c**, SUNCORR_Lo and control. Blue hatching indicates differences that are very likely (greater than 90% probability) to be significant according to the pairwise comparison test. Simulated JJA evapotranspiration difference (colour scale, mm d^{-1}) between **d**, SUNCORR_Hi and control; **e**, SUNCORR_Ad and control and **f**, SUNCORR_Lo and control.

questions dealing with future landscape modification, expected to layer additional stress onto an already sensitive system. We use the rapidly expanding Sun Corridor, whose 2000–2030 projected growth rate exceeds that of any other US megapolitan area[11], as a case study to explore the direct climate consequences of rapidly urbanizing megapolitan complexes.

Here we apply the Advanced Research (ARW) version of the Weather Research and Forecasting Model[14] (WRF), including an urban canopy model (see Methods and Supplementary Table S1), whose utility is well-established[15] and whose performance has been thoroughly evaluated over urbanizing regions of the semi-arid southwest[16], to investigate the climatic impacts of Sun Corridor expansion. We use scenario-driven projections of 2050 Sun Corridor expansion to represent urbanization-induced LULCC and use the US Geological Survey's National Land Cover Database 2006 (ref. 17) to represent the urban landscape of modern-day central Arizona. A suite of ensemble-based, multiyear, 20-km resolution simulations were carried out using present climate conditions while incorporating Maricopa Association of Governments (MAG)-projected high- and low-development Sun Corridor growth scenarios (see Methods; Supplementary Table S2). Urban pixels in the high-development scenario (SUNCORR_Hi) were based on a designation requiring a minimum number of MAG-projected dwelling units per unit area to meet urban criteria, resulting in a greater Sun Corridor spatial extent (that is, maximum extent); these pixels were converted to high intensity/commercial class (that is, maximum magnitude) within WRF. Urban pixels in the low-development scenario (SUNCORR_Lo) were based on a designation that required a maximum number of MAG-projected dwelling units per unit area to meet urban criteria, resulting in reduced Sun Corridor spatial extent (that is, minimum extent); these pixels were converted to low intensity residential class (that is, minimum magnitude) within WRF. In this fashion, our simulations accounted for the largest potential uncertainty range of Sun Corridor expansion and magnitude, and resulting impacts (see Methods and Supplementary Figs S1 and S2).

For both modern-day and Sun Corridor expansion scenarios, we carried out three-year (2006–2008) continental scale simulations at 20-km resolution, each with four independent realizations (each scenario comprises 12 years of numerical experiments) based on staggered initial start dates (see Methods and Supplementary Table S2).

To quantify the significance of simulated results, we use the pairwise comparison of individual realizations[18] from the various samples (four staggered start dates for each of three simulated summers). We define very likely (greater than 90% probability) statistically significant differences between urban-development scenarios and the control experiment as nine or more pairs of realizations resulting in warming exceeding 0.25 °C (for expansion scenarios) relative to the mean signal (see Supplementary Information).

Our focus is restricted to impacts on the summer season (JJA) as millions of the semi-arid region's inhabitants endure their highest heat-related stress levels during this time of year. The local maximum near-surface temperature warming resulting from expansion to SUNCORR_Hi approaches 4 °C, with large portions of Arizona experiencing warming in excess of 1 °C (Fig. 2a). Reduced warming (generally less than 0.5 °C) is evident over relatively smaller portions of the central USA, potentially associated with atmospheric hydrologic connectivity and redistribution of North American monsoon moisture[19]. To quantify potential adaptation impacts, we repeated all SUNCORR_Hi experiments with cool roofs by setting urban-roof albedo values in urbanized areas to an Environmental Protection Agency (EPA) Energy Star SOLARFLECT coating value of 0.88 (SUNCORR_Ad; see Methods). Cool-roof implementation reduces the warming influence of urban development considerably (Fig. 2b) in agreement with previous work demonstrating the urban-heat-island mitigation potential of this approach[20–23]. The preceding warming associated with expansion to SUNCORR_Hi over the central USA persists for this adaptation scenario, suggestive of potentially non-local consequences of large-scale, semi-arid, megapolitan expansion. We caution that the use of a Lagrangian model to track the trajectory of evapotranspired moisture is required to better characterize the potential teleconnection pathway[19] associated with large-scale urbanization. Although still indicating substantial warming, consideration of a lower Sun Corridor expansion scenario shows reduced impacts (Fig. 2c), with maximum local and regional scale warming of comparable magnitude to SUNCORR_Ad.

The conversion of permeable to non-permeable surfaces results in a substantial decrease in summer-time evapotranspiration, with local reduction exceeding 1 mm d^{-1} over urbanizing areas (Fig. 2d–f). Although cool-roof implementation does offset urban-induced warming by about half, the effects on evapotranspiration from this mode of adaptation remain at least as large as those from expansion to SUNCORR_Hi. Although warming resulting from expansion to SUNCORR_Ad and SUNCORR_Lo are similar in magnitude and extent, there seems to be much less impact on evapotranspiration resulting from the lowest urban-development scenario.

Sun Corridor expansion illustrates scenario-dependent urbanization impacts on mean summer-time near-surface temperature variance (Fig. 3). Expansion to SUNCORR_Hi leads to a decrease, indicative of a more narrow diurnal range and reveals the persistence and intensification of a phenomenon already noted in observations (Fig. 1a). The decrease in overall variance noted in expansion to SUNCORR_Hi persists for the adaptation scenario considered, highlighting the necessity of evaluating the merit of adaptation measures more comprehensively (that is, beyond an exclusive focus on mean temperature). Indeed, although a cooler mean climate is expected to prevail (relative to SUNCORR_Hi), the effects on evapotranspiration and impacts on the extent of the diurnal range are similar to the maximum expansion scenario and do not revert to their original (that is, pre-expansion) state. In the context of this approach, adaptation is only partly realized and future work is required to assess the environmental implications of decreased thermal variability and dryer near-surface conditions.

The warming influence of Sun Corridor expansion relative to mid-century impacts of long-lived greenhouse gases (LLGHGs) is assessed over areas in Arizona previously deemed very likely to be warmer relative to control (see Methods; Fig. 4a–c). As one measure of the relative importance of the investigated forcing factors, we computed the ratio of warming resulting from expansion to SUNCORR_Hi (that is, maximum urbanization) and SUNCORR_Ad (that is, maximum urbanization with adaptation) relative to a lower emissions trajectory (B1; that is, minimum climate change) and repeated the calculation for expansion to SUNCORR_Lo (that is, minimum urbanization) relative to a higher emissions trajectory (A2; that is, maximum climate change). Urbanization-induced warming relative to the B1 pathway, through mid-century, is several times greater over locales experiencing urbanization, exceeding 300% for expansion to SUNCORR_Hi. Impacts are reduced when considering alternative emissions scenarios (Supplementary Figs S3–S5). Urbanization-induced warming is drastically reduced for expansion to SUNCORR_Ad relative to the B1 emissions pathway. The magnitude of warming for this adaptation scenario remains locally non-negligible although the geographical extent of its thermal sphere of influence, defined here as warming that is at least 10% relative to similar impacts arising from LLGHGs, is constrained considerably (relative to SUNCORR_Hi). Contrasting the impacts of SUNCORR_Lo to the A2 emissions pathway underscores the important dependence of urban expansion relative to differing emissions trajectories. Through the end of the century (Fig. 4d–f) warming attributed to Sun Corridor expansion remains important although both the magnitude of local and regional scale impacts and the extent of the thermal sphere of influence remain dependent on the particular built environment and emissions pathway.

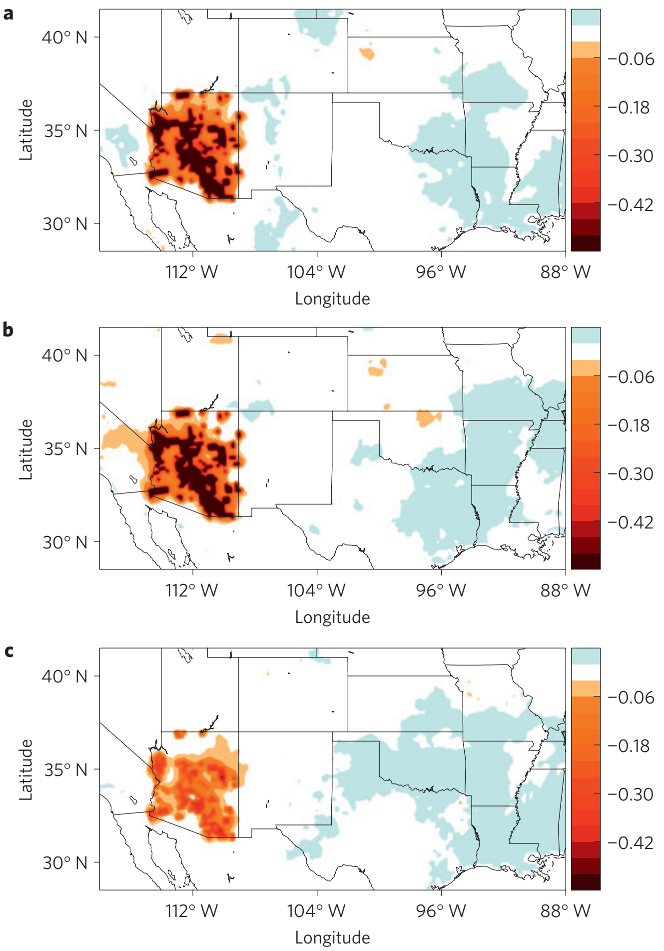

Figure 3 | Simulated summer-time two-metre air temperature variance differences. Simulated JJA two-metre air temperature variance difference (colour scale), normalized by control variance, between **a**, SUNCORR_Hi and control; **b**, SUNCORR_Ad and control and **c**, SUNCORR_Lo and control.

Any numerical modelling approach has inherent limitations and we recognize caveats relevant to our investigation. Although we consider our sensitivity results robust, we appreciate the value of a model intercomparison (for example, incorporating a range of urban-canopy schemes[24]) employing the methodology used here to improve diagnosis of simulated uncertainty associated with different parameterizations. Furthermore, it is important to point out that our approach does assume that a sample of three summers is sufficiently representative for comparison against 20-year means of climate change. This was a principal motivation for the execution of an ensemble of simulations, with four independent realizations, to reduce internal model noise and sensitivity to initial conditions. Finally, our comparison of urbanization-induced climate change relative to impacts from greenhouse gas emissions is based on the assumption that these agents operate independently and that dynamical interactions between them (for example, through hydrometeorological processes) are not accounted for. Although a

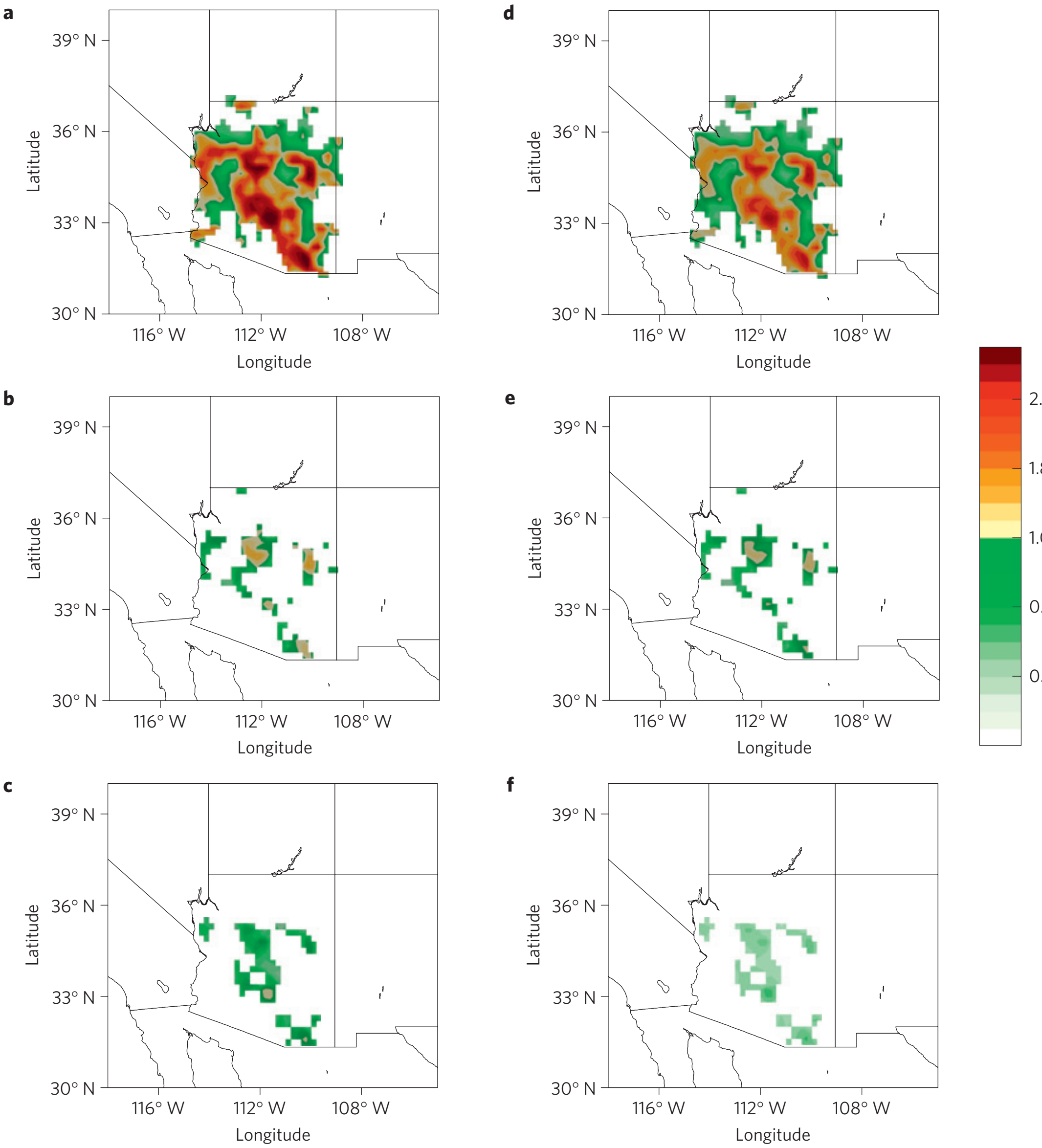

Figure 4 | Contribution of JJA urban-induced warming relative to projected JJA World Climate Research Programme Coupled Model Intercomparison Project phase 3 warming (relative to 1990–2010) resulting from increased emissions of LLGHGs. a, (SUNCORR_Hi minus control)/(B1 scenario: mean (2040–2060) warming); **b**, (SUNCORR_Ad minus control)/(B1 scenario: mean (2040–2060) warming); **c**, (SUNCORR_Lo minus control)/(A2 scenario: mean (2040–2060) warming); **d**, as **a** but relative to mean 2080–2100 warming; **e**, as **b** but relative to mean 2080–2100 warming; **f**, as **c** but relative to mean 2080–2100 warming.

natural next step will incorporate such coupled simulations, it does not reduce the significance of our work, which provides the first practically meaningful measure of the relative importance of each forcing agent, on local to regional scales, for the fastest growing megapolitan region in the USA.

According to present estimates, the global conversion of existing landscapes to urban land cover, by 2030, will result in as little new urban development as the surface area equivalent of California or as much as the surface area equivalent of the USA (ref. 25). Although we have shown that the climate impacts of Sun Corridor expansion are important, it is essential to recognize that megapolitan regions are growing collectively[11,26], each modifying their regional climate through alteration of the radiation and hydrologic balance. Sustainable megapolitan development will require incorporation of land-based mitigation strategies in addition to a continued focus on greenhouse gas emissions[4]. Such policies should target solutions aimed at overcoming challenges *vis-à-vis* the climate–energy–water nexus and require extension beyond just mean temperature impacts to provide guidance towards undeniably sustainable development paths.

Methods

WRF modelling system. WRF-ARW (version 3.2.1) is a state-of-the-art, fully compressible, non-hydrostatic Earth system model with wide-ranging utility, from urban-canopy-level modelling[15] to renewable-energy applications[27].

We used the four-layer (0–10 cm, 10–40 cm, 40–100 cm and 100–200 cm) Noah land-surface scheme[28], with recent improvements in snow-cover representation and energy-budget terms, to update soil temperature and moisture following the initial model timestep. The Noah land-surface model has been widely used in the climate modelling community (for example, in the development of the 25-yr North American Regional Reanalysis atmospheric and land-surface hydrology data set and also as part of the North American Regional Climate Change Assessment Program; http://narccap.ucar.edu/data/rcm-characteristics.html). We have used a recently modified version of the Kain–Fritsch convective parameterization scheme to represent subgrid-scale convective processes[29].

Urban-related processes are treated through use of the single-layer Noah urban-canopy model[15,30], which accounts for urban geometry, shadowing from and reflection of buildings, anthropogenic heating and roof, road and wall biophysical representation.

The geographic domain used in all experiments includes portions of the Atlantic and Pacific Oceans, southern Canada and northern Mexico and the contiguous USA (Supplementary Fig. S1). A full accounting of model options used is presented in Supplementary Table S1.

Initial and boundary condition data for this study are obtained from the Research Data Archive, which is maintained by the Computational and Information Systems Laboratory at the National Center for Atmospheric Research. The National Center for Atmospheric Research is sponsored by the National Science Foundation. The original data are available from the Research Data Archive (http://dss.ucar.edu) in data set number ds083.2 (US National Centers for Environmental Prediction). The National Centers for Environmental Prediction Final Analyses data are available globally beginning in 1999, have a 6-h temporal frequency and are placed on a $1^\circ \times 1^\circ$ grid.

WRF simulations. For both modern-day (control experiment) and Sun Corridor scenario experiments, we carried out three-year (2006–2008) continental scale simulations at 20-km resolution (Supplementary Table S1) spanning the contiguous USA and adjacent regions, each with four independent realizations (Supplementary Table S2). Realizations differ according to initial start time, with each scenario including a spin-up of three (realization 1), two (realization 2) and one month (realization 3), respectively, and a fourth realization without any spin-up. This approach is invaluable for the reduction of internal model noise and sensitivity to initial conditions and adds considerable confidence to the robustness of simulated results. Each scenario therefore comprises 12 years of numerical experiments, which are averaged to produce the corresponding scenario mean.

We use a Moderate Resolution Imaging Spectroradiometer-based 20-category landscape classification as the default land use and land cover (LULC) representation throughout the model domain, including urban cover where appropriate. For the control experiment, we use the US Geological Survey's National Land Cover Database 2006 (ref. 17) to represent the urban landscape of modern-day central Arizona (Supplementary Figs S1a and S2a).

To incorporate mid-century Sun Corridor expansion, we drew on MAG-generated 2050 scenario projections of statewide development. Analyses used land ownership and census information to develop scenarios of future state growth. To characterize the full range of potential impacts of Sun Corridor expansion and magnitude, we used MAG's minimum and maximum expansion scenarios. The minimum expansion scenario required a maximum number of dwelling units per unit area to meet expansion criteria, resulting in a spatially constrained development scenario (that is, SUNCORR_Lo). All Sun Corridor urban pixels experiencing transition to SUNCORR_Lo were converted to the lowest intensity urban LULC in the Noah urban-canopy model (Supplementary Fig. S1b). The maximum expansion scenario required a minimum number of dwelling units per unit area to meet development criteria, resulting in a spatially greater development scenario (that is, SUNCORR_Hi). All Sun Corridor urban pixels experiencing transition to SUNCORR_Hi were converted to the highest intensity LULC in the Noah urban-canopy model (Supplementary Fig. S1c). An adaptation scenario based on SUNCORR_Hi was carried out (SUNCORR_Ad) to evaluate the potential impacts of conversion to cool roofs. The EPA Energy Star SOLARFLECT coating value of 0.88 is lower than initial reflectivity after set-up and is appropriate after three years of wear and tear (EPA Energy Star roof product list: http://downloads.energystar.gov/bi/qplist/roofs_prod_list.pdf?8ddd-02cf; accessed 1 June 2011).

Urban-induced relative to LLGHG emissions warming. To project the degree of warming owing to increased levels of LLGHGs we obtained downscaled climate projection data derived from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 multimodel data set, stored and served at the LLNL Green Data Oasis (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). Multimodel projections corresponding to low (B1), medium (A1b) and high (A2) emission trajectories from 37, 39 and 36 general circulation models, respectively, of mean temperature change for 2040–2060 and 2080–2100 were obtained, and the degree of warming relative to 1990–2010 was calculated for each 20-year subset. Direct comparison against WRF simulations was made after mapping both data sets to a common resolution of 0.20°.

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Author contributions

M.G. carried out the numerical simulations. M.G. and M.M. carried out the analysis. M.G., M.M., A.M. and J.D. designed the study and wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.G.

Competing financial interests

The authors declare no competing financial interests.