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Mesoscale Climatic Simulation of Surface Air Temperature Cooling by Highly Reflective Greenhouses in SE Spain

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Supporting Information

ABSTRACT: A long-term local cooling trend in surface air temperature has been monitored at the largest concentration of reflective greenhouses in the world, at the Province of Almeria, SE Spain, associated with a dramatic increase in surface albedo in the area. The availability of reliable long-term climatic field data at this site offers a unique opportunity to test the skill of mesoscale meteorological models describing and predicting the impacts of land use change on local climate. Using the Weather Research and Forecast (WRF) mesoscale model, we have run a sensitivity experiment to simulate the impact of the observed surface albedo change on monthly and annual surface air temperatures. The model output showed a mean annual cooling of 0.25 °C associated with a 0.09 albedo increase, and a reduction of 22.8 W m^{-2} of net incoming solar radiation at surface. Mean reduction of summer daily maximum temperatures was 0.49 °C, with the largest single-day decrease equal to 1.3 °C. WRF output was evaluated and compared with observations. A mean annual warm bias (MBE) of 0.42 °C was estimated. High correlation coefficients ($R^2 > 0.9$) were found between modeled and observed values. This study has particular interest in the assessment of the potential for urban temperature cooling by cool roofs deployment projects, as well as in the evaluation of mesoscale climatic models performance.

1. INTRODUCTION

The largest concentration of reflective greenhouses on the planet is located in the coastal plains of the province of Almeria, SE Spain. The greenhouses sustain high efficiency horticulture.[1−3] Greenhouse farming development from 1970 through 2000 dramatically transformed the semiarid pasture land, and now, according to International Space Station personal, this area is the only human settlement that can be seen from the station with the naked eye. Since 2000, the total surface area of greenhouses has remained roughly constant at 27 000 ha (Supporting Information, SI, Figure S1).[4]

The development of greenhouse agriculture has led to a local long-term cooling trend in surface air temperatures at the area of −0.3 °C $decade^{-1}$, despite the generalized warming in the surrounding region (SE Spain) of +0.4 °C $decade^{-1}$.[5] The analysis of the observational records suggested that the increase in surface albedo associated with greenhouse development, +0.09 averaged over all seasons, has been the most probable cause of this cooling trend.

Urban heat islands, i.e., the difference in temperatures between urban and surrounding areas, can reach as much as 1° to 6 °C in summer months.[6] Urban albedo modification to cool local surface air temperature is a strategy already employed in many cities. For example, reflective roofs are required in certain situations in California and mandates have been proposed in the U.S. and Europe.[7,8] While the research community has used meteorological modeling to estimate the impacts of cool roofs requirements, no comparisons of modeled temperature changes to real world temperature changes occurring with citywide adoption of reflective roofs has been pursued to date (as citywide changes to roof characteristics are rare).

The albedo increase at the study area is employed here as an ideal and unique pilot experiment, where mesoscale modeling can be compared with field observations, helping to better determine the impact of albedo enhancement in future land cover change projects. Another advantage of this experience is that the net impact on global emissions of greenhouse farming has been quantified by life cycle assessment (LCA).[9] Because of all these interesting features, this particular farming model appears as a promising option to avoid competition between climate-change mitigation strategies based on land use, such as forestry and biofuels, and new demands for land to produce food for a growing population in the future.[10]

In this work, we pursue two goals: first, to demonstrate through modeling the mechanistic link between historic surface albedo increases and historic cooling trends observed in the area; second, to evaluate differences between observed and modeled temperature perturbations in order to inform future investigations of surface albedo enhancement strategies.

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Past modeling efforts and observational studies have investigated climatic alterations driven by land use/land cover changes at local, mesoscale, and regional scales.[11,12] In particular, previous modeling simulations show that albedo increases can cool surface air temperatures. For example, Betts used a global circulation model (HadAM3) to show that clearing of low albedo natural vegetation in Eurasian and American agricultural regions may have reduced annual mean temperatures in affected regions by 0.5−1 °C.[13] Other studies have used global models to simulate the effects of widespread urban albedo brightening through global deployments of cool roofs.[14−16]

In most cases, the low resolution of global models (0.5°-2.5°) limits the comparisons of model output to local field data. To evaluate the impact of albedo enhancements on urban scales, regional models with higher resolution and improved land surface representation can be employed. For example, simulations of ~0.1 albedo increases during short episodes (a few days) in several U.S. cities (Los Angeles, Atlanta, Detroit, Philadelphia Baltimore, Washington, and New Orleans), showed reductions in peak summertime temperatures ranging from 0.14 to 1.5 °C.[17] Temperature decreases of as much as 3.75 °C at single grid cells where simulated by urban albedo brightening in California using a slightly longer time frame of 5−7 days.[18] Other simulations from 1 to 6 days runs found up to 1−2 °C of peak temperature reductions could be achieved in New York[19] and Athens (Greece)[20] given varying increases of urban albedo.

In order to investigate feedbacks on the atmospheric system that may develop over longer periods and larger domains, simulations of urban albedo increases over 12 years with a domain covering the continental U.S. with 25 by 25 km sized grid cells showed year-round temperatures reductions in most cities with the largest cooling found at Los Angeles (−0.53 °C), Detroit (−0.39 °C), and New York (−0.3 °C).[21] In this work, it was assumed that albedo changes varied from 0.0 to +0.115, depending on urban density, according to previous estimations.[22] Over the long simulation period, some cities showed no significant temperature reductions, and a few regions downwind of urban areas showed small but significant temperature increases. Temperature increases were correlated with decreased cumulus precipitation, reduction in cloud cover, and increased shortwave radiation reaching the surface.

Some empirical studies have analyzed direct field observations to verify the impact of high albedo surfaces on air temperatures registered by monitoring stations. For instance, it was reported an average summer daytime cooling of 1−2 °C, for a +0.4 albedo difference between high albedo sandy surfaces and darker surrounding areas in New Mexico desert.[23] However, due to limited temporal and spatial coverage of reliable field data, few observational studies link long-term albedo changes and cooling trends. Land cover changes usually occur on decadal and longer time scales, such that the climatic signal requires observations over this time period.[12] Such observational studies are scarce, as reliable temperature series of at least 25−30 years are needed in order to establish climatic trends.[24] The impact on surface temperatures of land use changes from grasslands to intensive agriculture in the U.S. Great Plains was investigated using 7-years MODIS (Moderate Resolution Imaging Spectrometer) data, suggesting that differences in temperature might be due to irrigation but did not investigate the role of albedo change.[25]

We have selected a representative annual cycle (year 2005) to run both control and albedo enhancement simulations, and determine monthly and annual changes in surface air temperatures, as well as in the surface energy budget. This year was selected due to the availability of previous analyses[5] of surface temperatures and MODIS surface albedo data to further establish comparison between our results and these observational data. Two experiments were run for the same period and domain, changing only the albedo values in the land surface model to mimic either present greenhouses cover or previous pastureland cover. The scope of our sensitivity experiments is limited to assess the skill of WRF to simulate the impact of albedo changes on surface air temperatures in the area. All other biogeophysical and biogeochemical changes associated to historic land cover change in the study area have intentionally not been taken into account in order to focus on the potential of albedo enhancement for local adaptation of any human settlements to projected global warming.

2. MODELING METHODOLOGY

Climatic and Land Surface Model. The Weather Research and Forecasting Model (WRF) version 3.2.1 was used for simulations.[26] WRF is a mesoscale model designed to serve both operational forecasting and atmospheric research needs. The basic computations are based on solving the equations of motion, heat, and moisture and continuity. The model uses higher-order numerics and the dynamics conserves scalar variables.

The NOAH Land Surface Model (LSM) [27] has been coupled to WRF[28] and was used to simulate surface soil moisture, soil temperature, and canopy moisture. It provides surface fluxes and surface skin temperature as lower boundary conditions for a coupled atmospheric model. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometres.

WRF software architecture was built in CARVER IBM iDataPlex supercomputer at the US Department of Energy (DOE) National Energy Research Scientific Computing Center (NERSC) in Berkeley, CA. A 3-nested grid configuration was used, with grid sizes of 36, 12, and 4 km, respectively. The center-point of the coarse domain is located at the greenhouse farming area, 36.7 N and −2.7 W. The innermost domain (with 46 × 46 cells) covers the whole province of Almeria and part of neighboring provinces of Granada and Jaen, SE of Spain. The vertical dimension is divided onto 28 layers. Geographical data sets were downloaded from NCEP/NCAR.

In our WRF sensitivity experiments, we have used a "ceteris paribus" experimental approach, i.e., "holding all else constant", intentionally assuming no changes in other biogeophysical land cover properties and considering albedo as a single independent variable, so that the effect on the dependent variable (2-m temperature) can be isolated, thus focusing the model runs on the impact on surface air temperatures of observed historic albedo change in the area. [29]

The 24-category U.S. Geological survey (USGS) land use classification scheme was selected to provide land-cover data for the model domains. Greenhouse farming is not specifically represented in available land use schemes. Instead, the study area is still classified as USGS shrubland category (number 8), along with the rest of semiarid lowlands in the province of Almeria. This default category was selected to represent pre-existing pasture land (PS) in the area now covered by greenhouses, but albedo was modified and adjusted monthly

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Table 1. Mean Monthly and Annual Changes in Albedo, Surface Air Temperature, Net Solar Radiation, and Heat Flux at Surface[a]

	albedo change	$\Delta T2$ (°C)	ΔSWDOWN (W m^{-2})[b]	ΔHFX (W m^{-2})[c]	ΔT2/ΔSWDOWN
January	+0.07	−0.17	−8.60	−5.50	0.020
February	+0.06	−0.14	−8.50	−7.20	0.016
March	+0.09	−0.22	−17.3	−10.4	0.013
April	+0.10	−0.29	−27.6	−20.3	0.011
May	+0.09	−0.27	−26.8	−19.9	0.010
June	+0.12	−0.40	−41.3	−31.4	0.010
July	+0.12	−0.35	−42.1	−32.6	0.008
August	+0.13	−0.39	−39.7	−31.9	0.010
September	+0.13	−0.29	−30.5	−24.2	0.010
October	+0.09	−0.25	−15.9	−12.1	0.016
November	+0.06	−0.13	−7.80	−5.91	0.017
December	+0.07	−0.10	−7.90	−4.50	0.013
YEAR 2005	+0.09	−0.25	−22.8	−17.1	0.011

[a]Last column: ratio of temperature change per unit of net incoming radiation. [b]Change in net shortwave radiation. [c]Change in heat flux.

according to previous analysis of MODIS data.[5] To simulate albedo change in the area, a new greenhouses category (GH) was included in the scheme to represent present greenhouse farming land cover, and inserted in the pixels where greenhouses are located. Albedo was the only parameter that was changed in this new category, keeping the rest of USGS category "shrubland" default values unchanged. Time series of surface reflectance at 500 m resolution for the area of study were acquired from the MODIS instrument on board of the NASA Terra polar orbiting satellite for the year 2005. The Surface Reflectance product (MOD09A1) provides surface spectral reflectance estimates for bands 1−7 corresponding to 8 days composites removing atmospheric scattering and absorption effects.[30] The entire area of greenhouses farming located west of the city of Almeria (SI Figure S1) was selected as representative of greenhouse surface for monthly albedo determination. Currently, almost 70% of this coastal plain is covered by greenhouses, although the albedo data used here have been estimated for a parcel covering the whole area. This way, although the final albedo of an individual greenhouse can reach as much as 0.4, monthly and annual values were estimated averaging all greenhouses area.[5]

Model Runs. Model initialization data and boundary conditions were obtained from NCEP/NCAR Global Reanalysis 1 Data, GRIB1 format, 2.5° resolution, output frequency 6 h, 17 pressure levels (1000−10 hPa, excluding surface). Sea surface temperatures (SST) where updated daily during model runs, and were obtained from National Centers for Environmental Prediction/Marine Modeling and Analysis Branch (NCEP/MMAB) Real-Time SST archives (0.5° resolution and daily output frequency).

Two separated monthly WRF runs were carried on for the year 2005 over the 3 nested domains, with a spinup of 15 days each. Pasture (PS) simulations were run with default USGS land surface parameters, but albedo was adjusted monthly in the shrubland category, according to MODIS field data.[5] Average monthly albedo values from MODIS field data were inserted prior to every run at the two scenarios, high albedo (GH) and low albedo (PS). Greenhouses (GH) simulations were run inserting the field albedo values from MODIS in the pixels where greenhouses where located in the year of simulation. ARW-WRF 3.2.1 physics options selected are shown in SI Table S1.

Model Validation. Model performance was validated comparing WRF-GH output 2m-temperatures (T2) at the selected pixel against observations of near surface air temperatures registered at field station PAL (Las Palmerillas−Cajamar Foundation Research Station), located at 36°48′N, 2°43′W, inside the 4 × 4 km pixel at $x = 11$, $y = 22$ of the innermost domain. Another field station, Mojonera (MOJ) (Institute for Research and Training in Agriculture and Fisheries IFAPA, Junta de Andalucia) is also located inside this pixel, and lays just 1.8 km from PAL. Results were analyzed at the Almeria International airport station (AL), 36° 50′ N, 2° 21′ W, ~30 km from the main greenhouses development area. PAL and MOJ stations are included in the cooperative network of the Spanish Agencia Estatal de Meteorologia (AEMET), and AL station belongs to the Spanish official meteorological network. Raw data from both stations have been subjected to different quality controls, mostly gross error checks, internal consistency, temporal and spatial coherence. The method for model evaluation was adapted from previous ones.[31,32] Scatter plots between both daily and monthly observed and modeled temperatures were used as graphical displays to elucidate model performance. Linear regression slopes and correlation coefficients were calculated. Monthly and annual estimations of mean bias error (MBE), normalized bias error (MNBE), mean absolute gross error (MAGE), and normalized mean absolute gross error (MANGE) were calculated from modeled-observed pairs of 24 h averages. All analyses included a Student *t* test at the 0.05 significance level. Statgraphic Plus 4.1 was the software used for statistical analyses.[33]

3. RESULTS

Analysis of MODIS data indicated a 0.09 mean annual albedo increase from PS to GH averaged over all greenhouses farming area.[5] Albedo increased most during the summer, with a maximum monthly increase of +0.13 in August and September (Table 1). The lowest albedo increase (+0.06) was observed in the winter months of February and November.

At the greenhouses area, mean year-round surface temperature was 0.25 °C cooler in the higher albedo simulation (GH) than in the lower albedo scenario (PS), with average temperature decreases found in all months (Figure 1), ranging from 0.40 °C in June to 0.10 °C in December (Table 1). SI Figure S2 shows maximum daily temperatures in summer months (Jun−Jul−Aug) for both scenarios. Mean reduction of

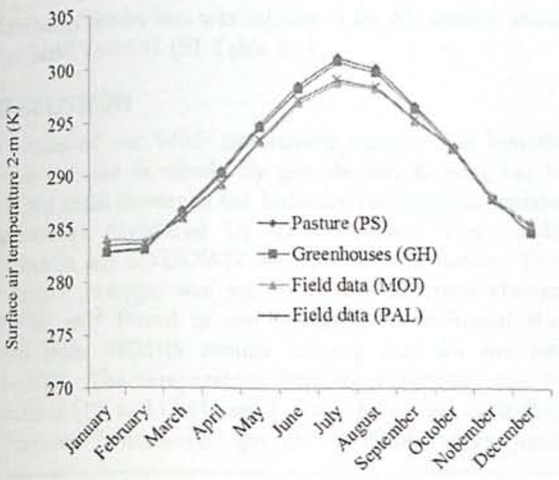

Figure 1. WRF-simulated mean monthly 2-m surface air temperature series in pasture and greenhouses scenarios (PS, GH), and observed field data from stations La Mojonera (MOJ) and Las Palmerillas (PAL). Year 2005.

maximum daily temperatures in summer was 0.49 °C. The largest decrease in daily maximum temperatures was 1.3 °C on July 16th, one of the three hottest days of the year. Daytime temperature differences were roughly twice night-time differences (SI Figure S3). Additionally, results where analyzed at AL station, ~30 km from the main greenhouse development area. As expected, the annual average temperature reduction between GH and PS scenarios was lower than at the study site surrounded by greenhouses (0.14 vs 0.25) (last column, SI Table S3).

For both scenarios, mean WRF simulated annual solar radiation (SWDOWN) reaching the surface was 223.9 W m^{-2}, and ranged from 344 W m^{-2} in July to 106 W m^{-2} in December. Changes to key energy budget components between the PS and GH simulations are shown (Figure 2). As expected,

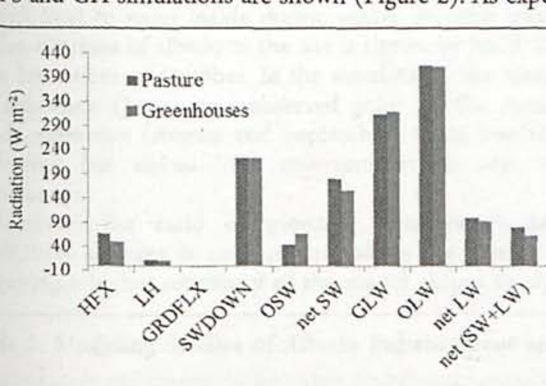

Figure 2. Mean annual change in surface energy budget components after albedo increase from pasture to greenhouses land use, year 2005. (HFX = Heat flux; LH = Latent heat; GRDFLX = Ground flux; SWDOWN = Incoming SW radiation; OSW = Outgoing SW radiation; Net SW = Net SW radiation; GLW = Incoming LW radiation; OLW = Outgoing LW radiation; and Net LW = net LW radiation).

increased surface reflectivity reduced net shortwave absorption at the surface, with a mean annual decrease of 22.8 W m^{-2} (Table 1). The largest reduction of net SWDOWN at the surface occurred in June (42.1 W m^{-2}), and the minimum in November (7.80 W m^{-2}). A similar pattern of seasonal change was observed for sensible heat fluxes (HFX), with a maximum reduction in July of 32.6 W m^{-2}, and minimum in December of 4.50 W m^{-2}. Mean year-round HFX decrease was 17.1 W m^{-2}. Latent heat (LH) changes were almost negligible, with a mean annual change of −0.8 W m^{-2}. Changes in the long wave (LW) radiation budget also had lower magnitudes than the shortwave components.

The changes in the diurnal cycles of net SWDOWN and HFX for a hot summer day (July 16th) are shown in SI Figure S4. Changes to HFX were found during daylight but were almost negligible at night. On July 16th, the average 24 h net SWDOWN (349 W m^{-2}) was reduced by 41.6 W m^{-2} (albedo was increased in the GH simulation +0.12 for July). Maximum values for net SWDOWN and HFX were seen at noon, 120.5 W m^{-2}, and 80 W m^{-2}, respectively.

To validate the model, simulated 2-m surface air temperatures (T2) were compared with field data from the PAL station. No statistically significant difference between the annual means of the model and observation records was found (95.0% confidence level, Student's *t* test). However, significant differences in standard deviations and variances were found, showing a larger degree of dispersion of model-estimated temperatures than of observed values (at 95% confidence level based on F-test). The scatter-plot between observed (PAL) and WRF-GH modeled daily averages of T2 is shown in Figure 3 (and for monthly values at SI Figure S5).

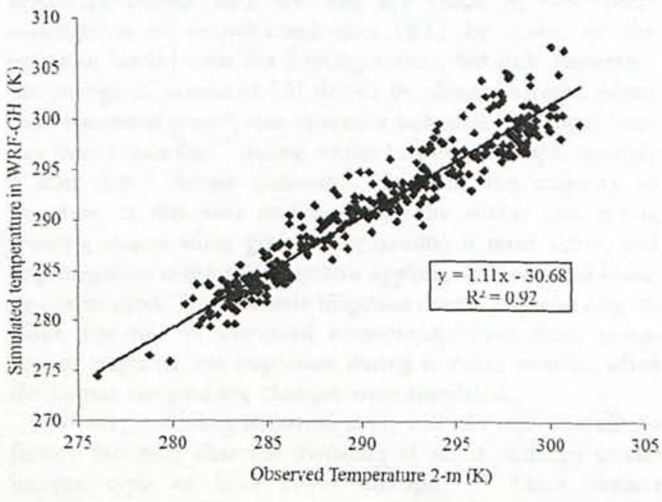

Figure 3. Scatterplot and linear regression equation of mean daily surface air temperature observations in PAL station and WRF-GH output (high albedo scenario).

The correlation coefficient was high for the daily means series (R^2 = 0.92), and even higher for monthly averages comparison (R^2 = 0.99). Linear regression slopes (significant at the 0.01 level based on a Student's *t* test) ranged around 1.0, with 1.11 ± 0.02 and 1.12 ± 0.02 for daily and monthly averages, respectively, suggesting a good match between simulated and observed values. Warm biases are suggested from the scatterplot for daily values above 296 K, in the summer temperatures range (Figure 3). Difference statistics for monthly values, MBE, MNBE, MAGE, and MANGE are shown in SI Table S2. Warm bias was detected in summer and spring months (March through September), while cold bias was shown in winter (October through February). Annual MBE was +0.42 °C, ranging from the coldest bias in December (−0.94 °C) to the warmest bias in July (+1.69 °C).

Additionally, model bias was calculated for AL station, showing higher MBE (+0.64) (SI Table S3).

4. DISCUSSION

The results of our WRF simulations support our hypothesis that the increase in albedo by greenhouses farming has been one of the main drivers of the historical reduction in surface air temperatures registered by field stations. The modeled reduction in net SWDOWN absorbed by the surface, 22.8 W m^{-2} annual average, was similar to the observed change of −19.9 W m^{-2} found in our previous observational study,[5] derived from MODIS remote sensing data for the period 2001–2005. The temperature differences between the WRF simulations (PS and GH) varied along the annual cycle (Figure 4). Farmers "whitewash" greenhouse roofs every June to alleviate excess heat inside during summer months. The slaked lime is later washed away at the end of September to allow enough light to enter inside during winter growing season. A sudden decrease of albedo in the site is shown by MODIS data from September to October. In the simulations, the maximum T2 difference (June) was observed prior to the maximum albedo difference (August and September) when insolation is decreasing but slaked lime still remains on top of the greenhouses.

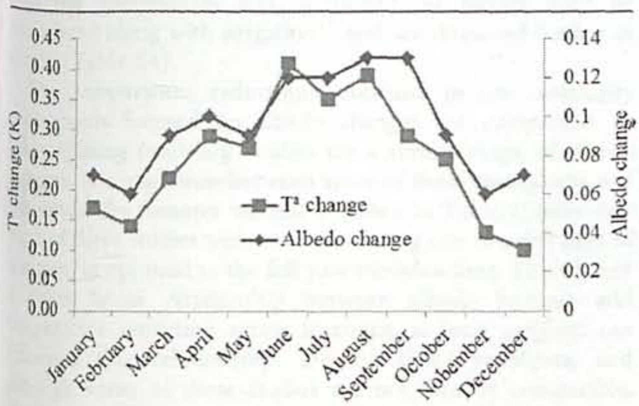

Figure 4. Monthly albedo differences and absolute values of mean air surface temperature change from high to low albedo scenarios (GH to PS simulations).

However, the ratio of monthly temperature to net SWDOWN changes is not constant along the annual cycle, suggesting a higher sensitivity of the model output to changes in radiation in winter, and lower values in summer (Table 1). This observation might be related to the seasonal variation in the partition between sensible to latent heat (Bowen ratio), with higher air moisture content in summer months.

Field data show that 2-m temperature at AL was 0.53 K warmer than PAL over the annual cycle (SI Table S3), raising the question: can the relative cooling in PAL compared to AL be attributed to greenhouses development? Simulated AL was 0.71 and 0.60 K warmer than PAL in the GH and PS annual simulations, respectively. The 0.11 difference between the two deltas indicates that only some of the difference in temperatures between AL and PAL can be explained by greenhouses development. Additionally, observed differences between AL and PAL were lowest in June when simulated differences peaked (SI Figure S6). The mismatch in timing of observed and simulated peak differences between AL and PAL may be somewhat explained by missed timing in whitewashing activities. However, the magnitude of the differences between simulated and observed monthly AL-PAL temperature gradients is larger than the modeled sensitivity to greenhouse albedo changes, indicating that fixing albedo characterizations would not be sufficient to remove the discrepancies.

The potential influence of irrigation on temperature reductions was intentionally not addressed in our modeling study. The values of latent heat (LH) change obtained in our WRF-GH output data are not the result of new parametrizations of evapotranspiration (ET) by crops, or the irrigation loaded onto the farming system, but only represents the change in simulated LH driven by albedo increase. Mean daily measured greenhouse reference potential ET ranges from less than 1 mm day^{-1} during winter to values of approximately 4 mm day^{-1} during summer.[3] However, the majority of irrigation in this area occurs during the winter and spring growing season when greenhouse farming is most active, and drip-irrigation is the major system applied, with reduced losses by evaporation. There is little irrigation during July and August. Thus, the role of increased evapotranspiration from greenhouses might be less important during summer months, when the largest temperature changes were simulated.

However, including irrigation alone will not represent all the factors that may alter the dynamics of moist enthalpy in this unique type of land cover change.[11,34] Land surface representations of local pasture and greenhouses agriculture are still far from being adequate, and many uncertainties remain. A full assessment of all of these changes would require

Table 2. Modeling Studies of Albedo Enhancement and Impact on Local Summer Temperatures (°C)

	albedo enhancement at pixel scale	peak T^a reduction one single summer day	average summer daily max T^a reduction	grid size[a] and location
this study	0.12	1.3	0.49	4 km^2, Almeria (Spain)
Taha (2008)[18]	0.15	2	N/A[b]	5 km^2 Los Angeles
Sailor (2003)[17]	0.1	0.14–0.58	N/A	2 km^2 U.S. cities
Synnefa et al. (2008)[20]	0.4	1.5	N/A	0.67 km^2 Athens (Greece)
Lynn et al. (2009)[19]	0.35	1–2	N/A	1.3 km^2 New York (U.S.)
Millstein and Menon (2011)[21]	0.02–0.11	0.02–0.5	[+0.27, −0.64]	Continental U.S.
Menon et al. (2010)[14]	0.01	N/A	0.03	0.5°, U.S.
Oleson et al. (2010)[15]	0.58 (roofs only)		0.5	1.9° × 2.5° global
Akbari et al. (2012)[16]	0.01	N/A	0.01–0.07[c]	global urban[d]

[a]Innermost domain of the simulation. [b]N/A = no data given. [c]Global annual temperature change (K). [d]Grid size non available.

further parametrization of the land surface model, particularly of greenhouses land cover properties. However, there is an absence of greenhouse observational data required to properly characterize key biogeophysical and biogeochemical properties and their representation in the land use model used for simulations, and thus adding a detailed parametrization of greenhouse agriculture was beyond the scope of this work. The focus on equivalent temperature or moist enthalpy as independent variable of these experiments is an interesting approach for the future assessment of overall changes in moist and heat content in the near atmosphere over the study area.[34] To estimate the net forcing caused by overall biogeophysical and biogeochemical changes that affect mesoscale climate, particularly changes in moist enthalpy and the seasonal partition between sensible and latent fluxes in the surface air over the greenhouses area, a number of factors must be considered along with irrigation[11] and are discussed further in the SI (Table S4).

The temperature reductions obtained in our sensitivity experiments focused on albedo changes are comparable to other existing modeling studies for a similar range of albedo increase. A comparison between some of these simulations and our results for summer months is shown in Table 2. Note that most of these studies were run only during one or a few days of summer, as opposed to the full year modeled here. There is not a direct linear relationship between albedo increase and temperature reduction across locations, as local variables can influence this relationship. Despite these variations, and although some of these studies are not directly comparable, all of them offer a common overview of the potential cooling that can be achieved by the implementation of albedo enhancement strategies.

Besides these considerations, the results of the WRF simulations reported here, along with the conclusion of previous empirical research at the study site[5] support the hypothesis that the increased albedo from greenhouse development has been one of the main drivers of historical temperature cooling in the area. Although these results respond to a very particular case of albedo enhancement by land cover change, they support the use of mesoscale meteorological modeling as a tool for predicting the effects of solar radiation management strategies, such as urban cool roofs, as local adaptation measures to warming and summer heat waves. Further improvements of land model parametrization stated above would help identify other factors associated to this particular land use change that might also be responsible of the observed cooling, in addition to albedo enhancement.

Feedbacks and other influences to the global climatic system were not addressed here. In this case, an approximation to the indirect climatic impact of greenhouses development, including an estimation of the net carbon footprint of greenhouse horticulture and CO_2 offsets equivalence of albedo increase, has been reported elsewhere.[9,35]

ASSOCIATED CONTENT

Supporting Information

Location of the study site, WRF simulated maximum daily surface temperatures in summer months, seven days averaged difference in hourly temperature from GH to PS simulations, changes in diurnal cycles of net incoming radiation and heat flux on one summer day, scatterplot of mean monthly observed vs simulated temperatures, and annual change in the monthly surface air temperature differences between two stations (PAL and AL) for observed temperatures, for high and low albedo simulations. Tables: physics and dynamics options used in WRF simulations, statistical measures for WRF output validation, comparison of simulated and observed temperatures at two locations, land surface properties to be considered in future research in the site. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. The authors contributed equally.

Notes

The authors declare no competing financial interest.

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