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Modelling and analysis of the impact of urban irrigation on land surface fluxes in the Los Angeles metropolitan area

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Abstract The current work includes developing and integrating an irrigation module within the Noah LSM-SLUCM (Single Urban Canopy Model) modelling framework. The model is run over a 49-km^2 urban domain in the Los Angeles metropolitan area at a high resolution (30 m) to understand the temporal variability and spatial heterogeneity of urban energy and water fluxes. The irrigation scheme developed is calibrated using residential water-use data and estimates of outdoor water consumption. Our results indicate that updating soil moisture to 75% of field capacity at a 6-day interval reasonably represents irrigation over this study region. To validate the model performance, we introduce a systematic evaluation process using MODIS-Landsat ET and Land Surface Temperature (LST) products as well as CIMIS- (California Irrigation Management Information System) based landscape ET observations. We conclude that addition of an irrigation scheme is critical to adequately simulate urban hydrological cycles, especially in arid and semi-arid regions.

Key words Noah; UCM; modelling; urban irrigation; land surface temperature; evapotranspiration

INTRODUCTION

Urban irrigation is a major component of the water cycle in many arid and semi-arid metropolitan areas where planted vegetation may not be adapted to the local climate and can require additional watering. Urban irrigation can influence the hydrological cycle by increasing available water for evaporation and infiltration and changing annual runoff ratios, primarily by contributions to dry season flows. With better understanding of the role of irrigation in hydrological cycles, water availability, and local patterns in hydrological fluxes, water management agencies will ultimately be able to: (a) examine future consumption scenarios, (b) ensure local potable sources despite possible future alterations in water supply, (c) maintain in-stream flow requirements for biota, and (d) manage developed ecosystems (Bhaskar & Welty, 2012).

Urban canopy models (UCMs) within land surface models (LSMs) are valuable tools for estimating water and energy cycles in urban settings. The coupled UCM/Noah/WRF (the community Weather Research Forecasting model) has been successfully applied over major metropolitan regions to reproduce the distribution and diurnal variation of urban heat island (UHI) intensity, diurnal variation of turbulent fluxes and wind speed and direction, small-scale boundary-layer horizontal convective rolls and cells, and nocturnal boundary-layer low-level jet streams (Miao *et al*., 2009a,b; Wang *et al*., 2009; Tewari *et al*., 2010; Loridan *et al*., 2010; Georgescu *et al*., 2011). Although Loridan *et al*. (2010) and Georgescu *et al.* (2011) recognized the importance of urban irrigation representation in highly urbanized sites, the majority of these studies do not represent the anthropogenic source of moisture in their study domains. The main objective of the current study is to incorporate an urban irrigation module into the Noah LSM-SLUCM (Single Layer UCM) modelling framework to assess the impact of urban irrigation on meteorological fields over the Los Angeles metropolitan area, with an initial focus on evapotranspiration (ET) and surface temperature patterns.

METHODS

A highly developed neighbourhood of approximately 49.0 km^2 on the west side of downtown Los Angeles is selected for this study. This area is composed of diverse land-cover types including industrial and commercial segments, residential regions with high and low densities, and a large park and several stadiums (fully vegetated pixels). To assess the impact of irrigation on urban meteorological fields, a new irrigation module was developed and incorporated into the Noah

LSM-SLUCM (Single Layer UCM) modelling framework. We first examine land surface fluxes and temperature sensitivity to the amount and timing of irrigation water added to the soil. Our tests show that accurately representing both the amount and timing of irrigation is critical for simulating urban irrigation and its effects on water and energy cycles. Next, a systematic validation approach for the framework developed is employed based on a previously developed MODIS-Landsat ET product (Kim & Hogue, 2012), Landsat Land Surface Temperature (LST), and reference ET (ET_0) from the California Irrigation Management Information System (CIMIS). The modelling system developed is run for Water Year (WY) 2004 and at a spatial resolution of 30 m to capture the heterogeneity of urban land use and take advantage of high resolution Landsat products (30 m).

Irrigation module development

Similar to a recent methodology proposed by Pokhrel *et al*. (2012), urban irrigation water sources are taken into account by increasing the soil moisture. Added irrigation water is a function of the soil moisture deficit, which is the difference between irrigated soil moisture content and actual soil moisture content. The following equations show how irrigated soil moisture content (SMC_{IRR}), soil moisture deficit (*DEF*), and irrigation water (*IRR*) are calculated for the vegetated portion of each grid pixel:

$$SMC_{IRR} = \alpha . SMC_{\max}$$

$$DEF = \max\left[\left(SMC_{IRR} - SMC_1\right), 0\right]$$

$$IRR = \frac{\rho_w}{\Delta t} DEF . D_1$$

$$\text{if} \quad DEF > 0 \rightarrow SMC_1 = SMC_{IRR}$$

where SMC_{max} is saturation soil moisture content or soil porosity; α represents irrigation demand factor which ranges from zero to one; D_1 is first soil layer thickness (10 cm); ρ_w is water density and Δt stands for Noah-SLUCM time step (1 hour). The irrigation module repeats the presented calculation for each time step; however, the top soil layer moisture content (SMC_1) is increased to the irrigated soil moisture content at a selected interval. For the current study, irrigation water is applied with several input scenarios: continuously (continuous irrigation), once a day, and every six days (pulse irrigations). The parameter α represents the amount of irrigation water added to the soil each time the module updates the soil moisture, simulating an irrigation event. Previous studies (Hanasaki *et al*., 2008a,b; Pokhrel *et al*., 2012) have suggested an irrigation demand factor of 1 for rice and 0.75 for other crops. In this analysis, 75% is chosen as the default α value for both continuous and pulse irrigation modules.

RESULTS

Estimating the irrigation requirements

Using the improved Noah LSM-SLUCM and outdoor water use estimates, the amount and timing of urban irrigation water is evaluated. Initially, three previously developed methods to approximate outdoor water consumption are used to separate total water use, provided by Los Angeles Department of Water and Power (LADWP), into its two components: indoor and outdoor water use. These approaches include: (a) a CDWR (California Department of Water Resources) estimate of outdoor water use (Pacific Institute, 2003), (b) a "minimum month" method, and (c) an "average month" method (Pacific Institute, 2003). For Los Angeles area, CDWR suggests outdoor water use makes up about 35% of residential water consumption (Pacific Institute, 2003). In the minimum and average month methods, respectively, the minimum water use month and the average of the three minimum months of water consumption over the study period are assumed to represent indoor water use. These values are then subtracted from LADWP total use data to approximate outdoor water use. Over our study area, the minimum and average month approaches result in outdoor water consumption rates equal to 28 and 31% of total residential water use for WY 2004, respectively.

To calibrate the introduced irrigation scheme, different irrigation timing scenarios are adopted, while the simulated irrigation demand factor is fixed at 0.75, and the results are evaluated against outdoor water use estimates. Table 1 presents a comparison of Noah LSM-SLUCM applied water using continuous, daily pulse, and 6-day pulse irrigation schemes with the three estimates of outdoor water use for WY 2004. Continuous and daily simulations suggest unrealistic irrigation application rates of 1.98 and 1.1 times the total water use (irrigation accounts for 198% and 110% of total water use), respectively. Irrigation with a 6-day interval, on the other hand, yields comparable irrigation rates (43% of total water use) to the outdoor water use estimates (ranging from 28 to 35% of total water use). Note that minimum and average month methods are reported to underestimate outdoor water use rates due to outdoor use during the winter period (Pacific Institute, 2003). We further evaluated a range of irrigation amount and timing scenarios (irrigation demand factor of 0.45, 0.55, 0.65, 0.85, and 0.95; watering interval of 2, 3, 4, 5, and 7 days; not presented). After examining the results, we advocate that updating the soil moisture to 75% of field capacity (demand factor of 0.75) at a 6-day interval provides a good approximation of urban irrigation within the study domain.

Table 1 Comparison of Noah LSM-SLUCM applied water over the study domain using continuous, daily pulse, and 6-day pulse irrigation schemes with the three estimates of outdoor water use for WY 2004. Values are % of total water use.

Irrigation water simulations		Outdoor water use estimates	
Continuous irrigation	198	CDWR estimate	35
Pulse irrigation, daily	110	"Minimum month"	31
Pulse irrigation, 6-day	43	"Average month"	28

Model evaluation

Guided by the initial analyses, the irrigation demand factor is set to 0.75 and irrigation is forced at a 6-day interval (one pulse every 6 days). Next, simulated ET and land surface temperature, with and without utilizing the modified irrigation module, are compared and evaluated against observed data (Figs 1 and 2). Figure 1 shows the comparison of the evapotranspiration and LST maps with the remote sensing products, MODIS-Landsat ET product (Kim & Hogue, 2012) and Landsat-based LST, for 4 May 2004. The maps present a 4 km × 4 km portion of our study domain which includes street networks and residential pixels (left side), fully vegetated cells (from several stadiums within the University of Southern California; middle-right), and industrial regions (right side). Compared to the remote sensing data, both simulated ET and LST results are improved when the established irrigation module is utilized. The ET and LST biases in fully vegetated and low intensity residential pixels are reduced from –81% to –5%, and from 8% to 4%, respectively. Moreover, remote sensing data and simulated results show similar patterns when urban irrigation is taken into account. The lower ET rates and higher LST values in the street and road networks, as well as the highest evapotranspiration rates and lowest land surface temperatures in the parks and low intensity residential areas, are clearly identifiable when the calibrated irrigation module is utilized. These patterns are hardly noticeable in the simulation with no irrigation.

To more fully examine the developed modelling framework, the monthly variability of simulated ET over fully vegetated areas, with and without inclusion of the developed irrigation scheme, is evaluated against CIMIS-based evapotranspiration observations (Fig. 2). First, a landscape coefficient of 0.65, suggested by CDWR (2000), is selected to convert CIMIS ET_0 data to landscape evapotranspiration. This coefficient and ET_0 data from six regional CIMIS stations are used to compute an interpolated urban landscape evapotranspiration, which is then employed in evaluation of the Noah-SLUCM (Fig. 2). Generally, model simulation with the irrigation module compares well with the CIMIS-based ET values. In contrast, the non-irrigation simulation underestimates ET rates consistently and significantly. The simulation with no irrigation shows the

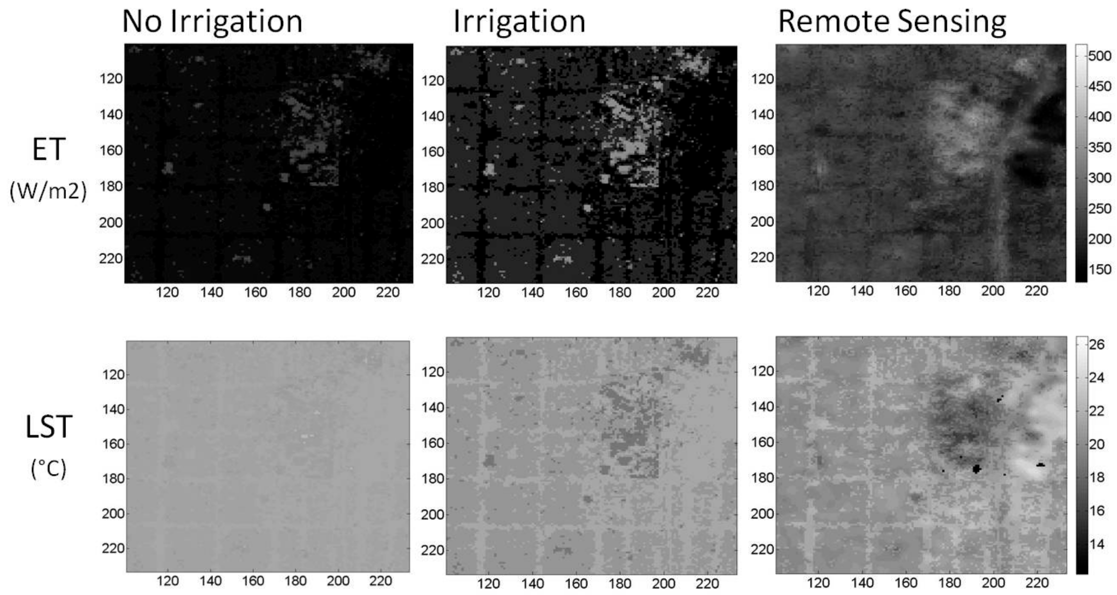

Fig. 1 ET (top) and LST (bottom) maps from simulations with (left) and without including irrigation (middle) and the MODIS-Landsat products (right), valid at 11:25 (local time), 4 May 2004.

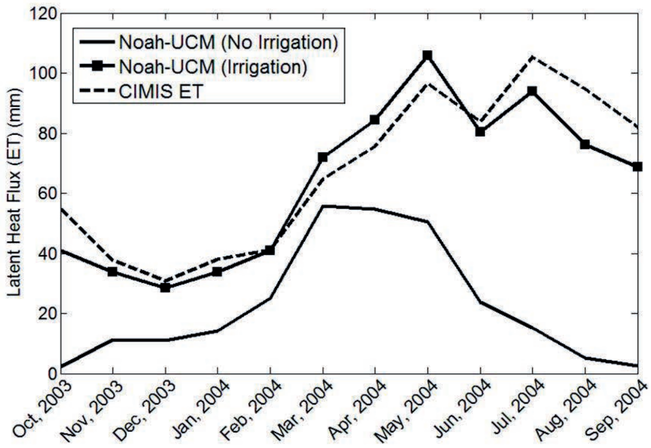

Fig. 2 Monthly time series of simulated ET over fully-vegetated pixels, with and without including irrigation, and their comparisons with the interpolated CIMIS based ET for water year 2004.

strongest biases during the summer months, while the irrigation simulation gives reasonable predictions of the CIMIS based ET. The evapotranspiration error for the non-irrigation simulation is –90 mm/month for July 2004, while this value reduces to –11 mm/month when the irrigation scheme is adopted (Fig. 2).

Impact of irrigation on water balance

Precipitation, irrigation water, ET, and surface and subsurface runoff results obtained from simulations, with and without irrigation, are compared over fully vegetated pixels for WY 2004 (Table 2). The study area received a total of 257 mm of precipitation during WY 2004, which is about 100 mm less than the long-term average (1949 to 2006; Western Regional Climate Center, http://www.wrcc.dri.edu). When compared to the non-irrigation simulation, the Noah LSM-SLUCM with irrigation produces a much higher ET rate. The surface runoff rate is not significant, even when irrigation water is added to the system. However, the irrigation-induced subsurface recharge is significant: 12.2 mm/year for non-irrigation simulation and 140.9 for the irrigation

Table 2 Simulated annual water budgets, before (No IRR) and after adding irrigation (IRR), over fully-vegetated pixels for WY 2004 (mm/year).

	No IRR	IRR
Precipitation	257.2	257.2
Irrigation water	0.0	621.4
ET	271.0	759.1
Surface runoff	7.2	11.8
Subsurface runoff	12.2	140.9

case. Table 2 indicates a 621 mm increase in annual hydrological inflow over grassy areas results in a 488 and 129 mm increase in evapotranspiration and groundwater recharge, respectively. In other words, over fully vegetated areas, 78% and 21% of extra water applied to the surface is lost to evapotranspiration and subsurface runoff, respectively.

To evaluate the simulated water budget, we compare the results with recent ET measurements in the Los Angeles area. Moering (2011) employed a previously developed chamber method to measure instantaneous ET and reported an annual evapotranspiration of about 1200 mm over irrigated parks for WY 2011. This value cannot be directly compared with our results because these ET measurements were carried out during a different water year with an annual precipitation amount of 556 mm, which is more than twice what our study domain received during WY 2004. However, during WY 2011, Moering (2011) reported the measured ET to be about 66% of CIMIS-based reference ET rates. For WY 2004, 66% of CIMIS-based ET_0 is equal to 814 mm, which compares reasonably well with the simulated evapotranspiration of 759 mm/year.

CONCLUSIONS

In this study, we develop, calibrate and systematically evaluate an irrigation scheme within the Noah LSM-SLUCM modelling system over a 49.0 km^2 study area in the Los Angeles metropolitan area. Guided by our sensitivity analysis, we note that accurately representing both the amount and timing of irrigation is essential for simulating urban irrigation and its effects on energy and water budgets. Using the LADWP residential water use data and the outdoor water use estimates, calibration analysis shows that the proposed irrigation scheme with an irrigation demand factor of 0.75 and irrigation interval of 6 days (one pulse every 6 days) reasonably represents irrigation fluxes over the study domain. Evaluated against the MODIS-Landsat ET and Landsat LST products as well as CIMIS-based landscape ET observations, the modelling results indicate that the Noah LSM-SLUCM can perform realistically over the Los Angeles area when a reasonable irrigation module is incorporated. However, without irrigation, the model produces large biases in surface fluxes simulations. This work strengthens the urban LSM framework with a sophisticated irrigation scheme that accounts for the essential role of anthropogenic water contribution in urban hydrologic cycles. The modelling system developed may be a useful tool for quantifying urban water fluxes, particularly in arid and semi-arid regions where imported water significantly impacts the local urban water budget.

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