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Modeling and Remote Sensing of Urban Land-Atmosphere Interactions with a Focus on Urban Irrigation

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Author
Vahmani, Pouya

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Modeling and Remote Sensing of Urban Land-Atmosphere Interactions with a Focus on Urban Irrigation

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Civil Engineering

by

Pouya Vahmani

2014
Urbanization is a demographic trend worldwide. It is found that half of all cities with populations greater than 100,000 are located in water stressed watersheds and are heavily dependent on imported water. Urban irrigation can exceed natural precipitation in these cities and is an important component of the water cycle. For instance, 14-30% of municipal water consumption in California is used for irrigation. Hence, understanding and quantifying the potential influence of urban anthropogenic soil moisture contribution on local and regional hydrological cycle is an imperative step toward sustainable and better managed water resources in water scarce regions.

The first part of current work examines the influence of irrigation on urban hydrological cycles through development of an irrigation scheme within the Noah Land Surface Model (LSM) -
Urban Canopy Model (UCM) system. The model is run at a 30-m resolution for a two year period over a study domain in the Los Angeles metropolitan area. A sensitivity analysis indicates significant sensitivity relative to both the amount and timing of irrigation on diurnal and monthly energy budgets, hydrological fluxes and state variables. Monthly residential water use data and three estimates of outdoor water consumption are used to calibrate the developed irrigation scheme. Model performance is evaluated using a previously developed MODIS-(Moderate Resolution Imaging Spectroradiometer)-Landsat evapotranspiration (ET) and Landsat Land Surface Temperature (LST) products as well as hourly ET observations through the California Irrigation Management Information System (CIMIS). Results show that the Noah LSM-UCM realistically simulates the diurnal and seasonal variations of ET when the irrigation module is incorporated. However, without irrigation, the model produces large biases in ET simulations. The ET errors for the non-irrigation simulation are -56 and -90 mm/month for July 2003 and 2004, respectively, while these values reduce to -6 and -11 mm/month over the same two months when the proposed irrigation scheme is adopted. Results also show that the irrigation-induced increase in latent heat flux leads to a decrease in LST of about 2 °C in urban parks. The developed modeling framework can be utilized for a number of applications, ranging from outdoor water use estimation to climate change impact assessments.

In the second part of this work we investigate the utility of remote sensing based surface parameters in the Noah-UCM for a more accurate representation of developed surfaces in this modeling framework. Landsat and fused Landsat-MODIS data are utilized to generate high resolution (30 m) monthly spatial maps of green vegetation fraction (GVF), impervious surface area (ISA), albedo, leaf area index (LAI), and emissivity in the Los Angeles metropolitan area. The gridded remotely sensed parameter datasets are directly substituted for the land-use/lookup
table based values in the Noah-UCM modeling framework. Model performance in reproducing ET and LST fields is evaluated utilizing Landsat based LST and ET estimates from CIMIS stations as well as in-situ measurements. Our assessment shows that the large deviations between the spatial distributions and seasonal fluctuations of the default and measured parameter sets lead to significant errors in the model predictions of monthly ET fields (RMSE= 22.06 mm/month). Results indicate that implemented satellite derived parameter maps, particularly GVF, enhance the Noah-UCM capability to reproduce observed ET patterns over vegetated areas in the urban domains (RMSE= 11.77 mm/month). GVF plays the most significant role in reproducing the observed ET fields, likely due to the interaction with other parameters in the model. Our analysis also shows that remotely sensed GVF and ISA improve the model capability to predict the LST differences between fully vegetated pixels and highly developed areas.

In the third part we explicitly address the impacts of urban irrigation by integrating the developed irrigation scheme within the coupled framework of the WRF-UCM over the semi-arid Los Angeles metropolitan area. We focus on the impacts of irrigation on the urban water cycle and atmospheric feedback in arid and semi-arid cities. Our objective is to build upon previous work, focusing on improving the representation of irrigated urban vegetated in the numerical weather prediction models which are now standard tools to study urban-atmosphere interactions. Our results demonstrate a significant sensitivity of WRF-UCM simulated surface turbulent fluxes to the incorporation of irrigation. Introducing anthropogenic moisture, the vegetated pixels show increased latent heat fluxes and decreased sensible and ground heat fluxes confirming irrigation induced shift in the energy partitioning toward elevated latent heat fluxes. The evaluation of the model performance via comparison against CIMIS based reference ET indicates that WRF-UCM, after adding irrigation, performs reasonably during the course of the
month, tracking day to day variability of ET with notable fidelity. In the absence of irrigation, simulated ET fluctuations are similar to the CIMIS based ET and irrigated case, in the first few days of simulations. Toward the end of the month, however, the differences between simulated ET and CIMIS based $ET_0$ become more significant in the not irrigated case. This is due to fact that, in the not irrigated simulation, the soil moisture is the only source of water in the absence of irrigation and significant precipitation. In the course of simulation, the soil moisture sorted in the soil layers is consumed, resulting in considerable decreases in the soil moisture levels in all layers. The soil moisture depletion leads to reduced latent heating and cooling effects of urban vegetation. Analysis of these results indicates the importance of accurate representation of urban irrigation in water scarce regions such as Los Angeles metropolitan area. Moreover, it is found that the initial soil moisture level plays a principal role in disguising the real impacts of irrigation in urban domains and to see the actual impacts of urban irrigation the simulations should be conducted for a longer period of time than one month which is rare in WRF-UCM studies.
The dissertation of Pouya Vahmani is approved.

William W-G. Yeh

Steven A. Margulis

Soroosh Sorooshian

Terri S. Hogue, Committee Chair

University of California, Los Angeles

2014
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I would like to thank my advisor Dr. Terri S. Hogue for her mentorship, guidance, support and advice that helped me enormously throughout this journey.

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EDUCATION

- **University of California, Los Angeles**
  
  *Ph.D. candidate* in Hydrology and Water Resources Eng.  
  Department of Civil and Environmental Engineering  
  GPA: 3.97

- **California State University of Los Angeles**
  
  *Master of Science* in Environmental Engineering  
  Department of Civil and Environmental Engineering  
  GPA: 4.00

- **Shahid Bahonar University of Kerman (Iran)**
  
  *Bachelor of Science* in Civil Engineering  
  Department of Civil and Environmental Engineering  
  GPA: 3.34

AWARDS AND HONORS

- IAHS Best Early Career Scientist Paper Award, the Gothenburg Assembly, 2013.
- NASA Earth System Science Fellowship (NESSF), University of California, Los Angeles, 2012 and 2013.
- Bridge to the Doctorate Fellowship, the Center for Energy and Sustainability/California State University, Los Angeles, 2010.
- Special Recognition in Graduate Studies, CSULA 2010 Honors Convocation.
- Outstanding Poster Presentation Award in Engineering, 2010 CSULA Student Symposium
- Graduate Student Fellowship, the Center for Energy and Sustainability/California State University, Los Angeles, 2009.
- Graduate Student Scholarship, Shahid Bahonar Uni. of Kerman (Iran), 2006.
- First Ranked Graduating Student in Civil Eng. Class, Shahid Bahonar Uni. of Kerman (Iran), 2006.

RESEARCH EXPERIENCE

- **University of California, Los Angeles**
  
  *Graduate Student Researcher*  
  Performed research on Land surface modeling, Urban-atmosphere interactions, and Remote sensing applications in Hydrology and Water Resources.

- **California State University of Los Angeles**
  
  *Graduate Student Researcher* at the Center for Energy & Sustainability  
  May. 2009 - Jun. 2010  
  Performed research on Soil Weathering due to CO₂ exposure and other Environmental Engineering research projects.
PROFESSIONAL AFFILIATIONS AND SERVICE ACTIVITIES

- Manuscript Reviewer: Urban Climate
- Society Member: American Meteorological Society
- Society Member: American Geophysical Union
- Society Member: American Society of Civil Engineers

PUBLICATIONS/CONFERENCE PRESENTATIONS

  - Development and Validation of the Noah-Urban Canopy Model for Two Distinct Urban Climates in the Los Angeles Basin, *poster* presented at the *AGU Fall Meeting 2011*.
  - Microtextural analysis of weathering in CO₂ saturated soils, *poster* presented at the *Spring ACS National Convention, 2010*.

TEACHING/WORK EXPERIENCE

- From Jan. 2011 to March 2011, Civil and Environmental Engineering, UCLA, California, Teacher Assistant: *Introduction to Water Resources Engineering*, Gave lectures once a week, held office hours 4 hours a week, and designed the assignments and tests.

SKILLS

- Expertise in *MATLAB, Fortran, Unix/Linux, HTML*, and *CSS*.
- Could operate effectively with *ArcGIS, MODFLOW, AutoCAD*, and *Microsoft office*. 
Chapter 1. Introduction

1.1. Problem Statement

Urbanization is a demographic trend worldwide. More than half of the world's population inhabited cities in 2008 and it is expected that more than 80% of the global population will reside in urban areas by 2030 [UNFPA, 2007]. It is found that half of all cities with populations greater than 100,000 are located in water stressed watersheds [Richter et al., 2013]. These cities, particularly ones located in arid and semi-arid regions (e.g., Phoenix, Arizona, Los Angeles and San Diego, California), are heavily dependent on imported water as the local supplies are exhausted [Richter, 2013] or under-utilized. Urban irrigation is an important component of water cycles in these regions where planted vegetation may not be adapted to the local climate and requires additional watering. For instance, 14-30% of municipal water consumption in California is used for irrigation [Gleick et al., 2003]. Residential areas within the city of Los Angeles are estimated to consume about 225 million cubic meters per year for irrigation [LADWP 2000, 2001]. In such regions, anthropogenic moisture applied to the landscape can exceed natural precipitation [CDWR 1975]. Hence, understanding and quantifying the potential influence of urban anthropogenic soil moisture contribution on local and regional hydrological cycle is an imperative step toward sustainable and better managed water resources in water scarce regions.

The Weather Research and Forecasting (WRF) model [Skamarock et al. 2008], a regional atmospheric model, has been widely used for simulation of urban-atmosphere heat, moisture, and momentum exchanges since the single layer UCM [Kusaka et al., 2001; Kusaka and Kimura, 2004] was installed within Noah LSM in this modeling framework. The main focus of the UCM developers has been to improve the simulation of thermodynamics, dynamic and thermal storage
effects in urban canyons, by incorporating the buildings' role in trapping and reflection of shortwave and longwave radiation. Many studies have shown benefits of using WRF-Noah-UCM modeling framework to better understand the impacts of urbanization on the climate, meteorological fields in the lower atmosphere, and urban heat islands [Feng et al., 2012; Flagg and Taylor, 2011; Wang et al., 2013]. Few urban simulation studies have focused on the effects of canyon vegetation on the surface temperature and turbulent fluxes [Loughner et al., 2012; Lee and Park, 2008]. Although some studies recognized the lack of urban irrigation representation as a deficiency that the urban canopy modeling faces [Loridan et al., 2010; Georgescu et al., 2011], very few modeling studies account for the anthropogenic source of moisture in their study domains.

Remote sensed observations provide complementary information to modeling studies over urban areas. For instance, remote sensing data is used to characterize urban-induced physical modifications to the Earth's surface [Jin and Shepherd, 2005]. Airborne LIDAR (Light Detection and Ranging) systems and photogrammetric techniques have been utilized to produce morphological parameters over urban areas [Burian et al., 2004, 2006, 2007; Taha, 2008; Ching et al., 2009]. Observations from satellites have been also utilized in model validation processes over urban areas [Giannaros et al, 2013; Miao et al., 2009]. In addition to in situ observations, Giannaros et al. [2013] included MODIS based LST products in their modeling study of the urban heat island over Athens, Greece. Similarly, Miao et al. [2009] utilized 1-km resolution MODIS data to verify the WRF-Noah-UCM simulated LST distribution in Beijing. Other studies have employed satellite data to replace outdated urban land use maps in atmospheric models with new remote sensing products [Cheng and Byun, 2008; Cheng et al., 2013]. Although these and other previous studies [e.g., Jin and Shepherd, 2005] have recognized the usefulness of satellite
imagery (e.g., NASA’s Terra, Aqua, and Landsat data) in specifying surface physical characteristics in urban environments, very few have directly incorporated high resolution gridded satellite based parameters (e.g., impervious surface area, albedo, and emissivity) into parameter estimation within land surface-atmospheric modeling systems.

1.2. Research Objectives and Research Questions

Our objective is to build upon previous work, focusing on improving the representation of developed surfaces and irrigated urban vegetation in numerical weather prediction models. We pursue this goal by developing a sophisticated and realistic irrigation module and making use of remote sensing based parameter sets within the WRF-Noah-UCM which is now a standard tool used to study urban-atmosphere interactions. The enhanced modeling framework will potentially improve our understanding of urbanization impacts on the boundary layer processes, near surface meteorological fields, and local and regional climate as well as water resources. A key question relates to physical mechanisms and components that define urban water budget in water scarce regions. With evaluating the role of irrigation in the urban water cycle and a focus on urban ET, this work is likely to shed further light on water cycle dynamics of urban complexes in arid and semi-arid regions.

The primary science questions addressed in this research are:

- What is the role of urban irrigation in the water cycle dynamics of semi-arid cities such as Los Angeles?

- How well can an improved Noah LSM-UCM modeling framework perform over developed areas?
- How well do the default parameter sets within Noah LSM-UCM modeling framework define the unique characteristic of Los Angeles land surface? Does the use of monthly gridded remote-sensing based parameter sets enhance the model’s predictive capabilities?

- What impacts urban irrigation representation in numerical weather prediction models (e.g. WRF) has on the predicted urban water cycle and atmospheric feedback in arid and semi-arid cities?

1.3. **Research approach**

To address the science questions and understand the water cycle dynamics in semi-arid cities, the following research framework is proposed:

The primary objective of the first part (Chapter 2) of the current study is to develop an integrated modeling framework to assess the impact of irrigation on urban meteorological fields over the Los Angeles metropolitan area with an initial focus on ET and surface temperature patterns. To facilitate this work, we incorporate a new irrigation module into the Noah LSM-UCM. We utilize monthly residential water consumption data for calibration of the proposed irrigation scheme. We also employ a systematic validation approach of the developed framework using a previously developed MODIS-Landsat ET product [Kim and Hogue, 2008; 2012; 2013], Landsat LST, and hourly reference ET ($ET_0$) from the CIMIS stations. To capture the heterogeneity of urban land use and take advantage of high resolution Landsat products (30 m) and water consumption data (block level) the developed model is run at a spatial resolution of 30 m. Results from this work are published in the Journal of Hydrometeorology [Vahmani and Hogue, 2014a].
In the second part (Chapter 3) we investigate the utility of remote sensing based surface parameters in the Noah-UCM modeling framework over a highly developed neighborhood in Los Angeles metropolitan area. Among parameters that can be related to a measurable physical quantity, we evaluate those routinely and freely obtained from satellite-based platforms. The derived parameter sets are implemented in the Noah-UCM with a focus on simulated surface energy and water cycles that are essential feedback to the widely used WRF model. Landsat and fused Landsat-MODIS data are utilized to generate high resolution (30 m) monthly spatial maps of green vegetation fraction (GVF), impervious surface area (ISA), albedo, leaf area index (LAI), and emissivity in the Los Angeles metropolitan area. The temporal and spatial distributions of newly assigned parameters are compared with those based on the model lookup tables. Next, gridded remotely sensed parameter datasets are directly incorporated into the Noah-UCM modeling framework replacing the land-use/lookup table based values. The sensitivity of the simulated energy and water fluxes to the newly developed spatial metrics of parameters is presented. The model's performance in reproducing ET and LST fields is evaluated utilizing Landsat based land surface temperature and ET estimates from CIMIS stations as well as in-situ measurements. Finally, the influence of each parameter set on the urban energy and water budgets is investigated. Results from this work have been submitted for publication in the Journal of Hydrology and Earth System Sciences [Vahmani and Hogue, 2014b].

In the third part (Chapter 4) we explicitly address the impacts of urban irrigation by integrating the developed irrigation scheme in Chapter 2 within the coupled framework of the WRF-UCM over the semi-arid Los Angeles metropolitan area. We focus on the impacts of irrigation on the urban water cycle and atmospheric feedback in arid and semi-arid cities. Our objective is to build upon previous work, focusing on improving the representation of irrigated urban vegetated in the
numerical weather prediction models which are now standard tools to study urban-atmosphere interactions. The enhanced modeling framework will potentially improve our understanding of urbanization impacts on the boundary layer processes, near surface meteorological fields, and local and regional climate. We are planning to submit the results from this work for publication in the Journal of Geophysical Research by June 2014.

1.4. References


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Chapter 2. Incorporating an Urban Irrigation Module into the Noah Land Surface Model Coupled with an Urban Canopy Model

2.1. Introduction

Increasing municipal water use has raised interest in improved understanding of the urban water balance, especially in rapidly urbanizing regions where imported water is a significant portion of the water budget [USDA 2007; Gober and Kirkwood 2010; Bhaskar and Welty 2012]. Irrigation is an important component of water cycling in semi-arid cities where planted vegetation may not be adapted to the local climate and requires additional watering. In such regions, anthropogenic moisture applied to the landscape can exceed natural precipitation [CDWR 1975]. Residential land types, with irrigated vegetation, generally demand the largest volume of water [Grimmond and Oke 1986]. Mayer and DeOreo [1999] provided data on the end uses of water in residential settings in twelve cities across the continent. They estimated that 58 percent of residential water use is for outdoor purposes (residential landscapes, swimming pools, etc.) over all study sites, and the value rises to 67 for locations in hot climates. Residential areas within the city of Los Angeles are estimated to consume about 225 million cubic meters per year for irrigation [LADWP 2000, 2001]. Understanding and quantifying the potential influence of urban anthropogenic soil moisture contribution on local and regional hydrological cycle is an imperative step toward sustainable and better managed water resources in water scarce regions.

Urban canopy models within land surface models can be employed to quantify water and energy cycle fluxes in urban settings. A range of studies [Chen et al. 2004; Holt and Pullen 2007; Lin et al. 2008; Kusaka et al. 2009; Miao et al. 2009a, 2009b; Loridan et al. 2010; Georgescu et al. 2011] have utilized the coupled UCM/Noah/WRF (The community Weather Research
Forecasting model) modeling framework over major metropolitan regions (e.g. Beijing, Houston, New York City, Taipei, Tokyo, Marseille, and Phoenix) to evaluate the model’s ability to reproduce the distribution and diurnal variation of urban heat island intensity and turbulent fluxes as well as wind, temperature, and humidity in the boundary layer. However, the majority of studies do not represent anthropogenic moisture sources in their study domains. Loridan et al. [2010] recognized the lack of urban irrigation representation as a deficiency that the urban canopy modeling faces in highly urbanized sites. Their study highlighted that this limitation affects the partitioning of turbulent energy between latent and sensible heat. Some efforts have been made to balance the insufficient representation of urban moisture: Loridan et al. [2010] chose a vegetation type with a low stomatal resistance (e.g. 'cropland mosaic' or 'grassland'); Georgescu et al. [2011] set the second (10-40 cm depth) and third (40-100 cm depth) soil layers, for the low-intensity residential class, to a reference soil moisture below which transpiration begins to stress.

Several water balance studies [Mitchell et al., 2001; 2008; Jarvi et al., 2011] have accounted for urban irrigation when applying the principle of mass conservation in the hydrological cycle of the studied urban domain. Mitchell et al. [2001] developed a water balance model (Aquacycle) by including water supply, wastewater, and storm water within a modeling framework. To mimic the effects of irrigation, the Aquacycle model keeps soil moisture at a specific minimum content required to maintain the desired garden condition or plant growth rate [Mitchell et al., 2001]. Over Canberra, Australia, Mitchell et al. [2008] illustrated that changes in irrigation water alter imported water, storm water, and evapotranspiration terms in the simulated water budget. Jarvi et al. [2011] developed an urban energy and water balance scheme with the advantage of requiring a limited number of measured meteorological variables and surface characteristics. The model
calculates irrigation water utilizing a simple hourly model and diurnal water profiles collected by Grimmond et al. [1996] over Los Angeles. The authors took into account the method of irrigation (automatic and manual) and reported a good agreement between measured and modeled irrigation rates. Mitchell et al. [2001] and Jarvi et al. [2011] highlighted that irrigation is a key component of urban water cycle, particularly in arid regions. Although these water balance analyses have been successfully applied to investigate the impact of irrigation on hydrological cycle, weather, and climate, none have explicitly addressed the issue of urban irrigation impacts within the framework of an urban LSM.

The primary objective of the current study is to develop an integrated modeling framework to assess the impact of irrigation on urban meteorological fields over the Los Angeles metropolitan area with an initial focus on ET and surface temperature patterns. To facilitate this work, we incorporate a new irrigation module into the Noah LSM-UCM. We utilize monthly residential water consumption data for calibration of the proposed irrigation scheme. We also employ a systematic validation approach of the developed framework using a previously developed MODIS-Landsat ET product [Kim and Hogue, 2008; 2012; 2013], Landsat LST, and hourly reference ET (ET$_0$) from the CIMIS. To capture the heterogeneity of urban land use and take advantage of high resolution Landsat products (30 m) and water consumption data (block level) the developed model is run at a spatial resolution of 30 m. Development, evaluation, and application of the integrated modeling framework are presented as follows.

2.2. Study Domain

Los Angeles is the 2nd largest metropolitan area in the U.S., currently home to 13 million residents, nearly 8% of the U.S. population [United States Census Bureau,
http://www.census.gov]. The city covers approximately 1,291 km² and is one of the most highly-urbanized and least green cities in the country [LA Times, July 20, 2008]. The region has a Mediterranean climate, receiving on average around 38 cm (15 inches) of rainfall per year [NOAA-CSC 2003]. Large inter-annual variations in the region’s climate are driven by ENSO (El Niño-Southern Oscillation) phenomenon, where the positive phase (El Niño) is typically associated with enhanced wintertime rainfall [NOAA-CSC 2003]. Offshore flows along the Southern California coast also have significant influence on the Los Angeles urban climate [Conil and Hall 2006]. Los Angeles contains highly variable and altered landscapes as well as extensive impermeable land cover. Like many semi-arid cities, the majority of vegetation in the city is non-native and well-watered [Bijoor et al. 2012], making the consideration of anthropogenic soil moisture contribution imperative.

Irrigation water in the Los Angeles metropolitan region is generally from imported water sources outside the basin. The majority of City water comes from the Colorado River (52%) and Los Angeles Aqueduct (36%) [LADWP 2010]. Local production wells, generally outside the city limits, supply a much smaller percentage of the city’s water (11%) [LADWP 2010]. There are very few private or domestic wells within the City boundary.

A highly developed neighborhood of approximately 49.0 km² (7×7 km) on the west side of downtown Los Angeles (Figs. 1 and 2) is used to test the Noah-UCM applicability in estimating urban ET variations and land surface temperature after introducing a new irrigation scheme. This study area is composed of diverse land cover types including industrial segments, major freeways (I-10 and I-110) and streets, residential regions with different densities, a large park and several stadiums (within University of Southern California) (Fig. 2a). Altogether, this area represents a cross section of typical land cover in the city of Los Angeles. The study domain
includes extensive industrial and commercial land cover, including freeways and streets, and amounts to 34\% of the total land cover (Figure 2b). High and low intensity residential land covers are 56\% and 8\%, respectively, of the study area. Finally, parks and grasslands cover 2\% of the total area.

Figure 1. NOAA C-CAP Land Cover map of the greater Los Angeles area with study domain (white box). Six CIMIS, seven NCDC, and 41 LADPW stations are shown as white circles, squares, and stars, respectively.
Figure 2. Study domain (7x7km) including: (a) Google image, (b) Noah LSM-UCM urban classification derived from C-CAP Land Cover map.

2.3. Observational Data

A range of datasets at various temporal and spatial resolutions are used to calibrate and evaluate the developed Noah-UCM modeling framework (Table 1). Single-family residential water use data at the census block level was provided by the Los Angeles Department of Water and Power (LADWP) and is used to calibrate the developed irrigation scheme. Residential (both high and low intensity) neighborhoods with single family fraction of 80% or more are included in the calibration processes. Selected neighborhoods are randomly distributed in the domain and cover 531,000 m² containing about 600 homes. The water delivery data is prorated by the agency to determine monthly water consumption (from 60-day reading/billing data) at the census block level. LADWP water data is separated into its two components: indoor and outdoor water use. Residential outdoor water use is influenced by many factors including sociodemographic
characteristics, economic conditions, housing and landscape patterns, urban vegetation, and local climate [Guhathakurta and Gober 2007; Harlan et al. 2009; Schleich and Hillebrand 2009; House-Peters et al. 2010]. Regional variability in these factors and limited metering introduce significant uncertainties in estimates of outdoor water use [Pacific Institute 2003]. In the current study, three established methods are employed to approximate outdoor water consumption from total water use for each census block: 1) a CDWR (California Department of Water Resources) estimate of outdoor water use [Pacific Institute 2003], 2) a "minimum month" method, and 3) an "average month" method [Pacific Institute 2003]. CDWR [1998] used simple assumptions of indoor to outdoor use proportion, types of billing periods, and other data collected by water agencies to estimate outdoor residential water use in different parts of California. The established model estimates outdoor water use makes up about 35% of residential water consumption in Los Angeles area [Pacific Institute 2003]. In the minimum and average month approaches, on the other hand, the minimum water use month and the average of the three minimum months of water use over the two year study period are assumed to represent indoor water use, respectively. These values are then subtracted from LADWP monthly records to estimate outdoor water consumption.

A recently developed UCLA ET model [Kim and Hogue, 2008; 2012; 2013] is adopted to retrieve ET at a daily time scale and 30m spatial resolution. The model is based on the SEBAL approach [Bastiaanssen et al. 2002; 2005] but utilizes remote sensing products (both MODIS and Landsat) to derive radiation products and the resultant evaporative fraction, ultimately producing a daily, 30m ET value. The ET product, along with 30m Landsat land surface temperature (or skin temperature) on the Landsat overpass days at 1125 local time, are used to evaluate model performance.
Table 1. Study datasets at various temporal and spatial resolutions used to force, calibrate, and evaluate the developed Noah-UCM modeling framework.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Temporal Resolution</th>
<th>Spatial Resolution / Number of Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Calibration</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Water Use</td>
<td>LADWP</td>
<td>Monthly</td>
<td>Block Level</td>
</tr>
<tr>
<td><em>Evaluation</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote Sensing Based ET</td>
<td>MODIS-Landsat</td>
<td>Daily</td>
<td>30 m</td>
</tr>
<tr>
<td>Remote Sensing Based LST</td>
<td>Landsat</td>
<td>Every 16 days</td>
<td>30 m</td>
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<tr>
<td>Ground Based ET</td>
<td>CIMIS</td>
<td>Hourly</td>
<td>6 Stations</td>
</tr>
<tr>
<td><em>Forcing</em></td>
<td></td>
<td></td>
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<tr>
<td>Ground Based Wind Speed, Air Temperature, Relative Humidity, and Air Pressure</td>
<td>NCDC</td>
<td>Hourly</td>
<td>7 Stations</td>
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<tr>
<td>Ground Based Solar Radiation</td>
<td>CIMIS</td>
<td>Hourly</td>
<td>6 Stations</td>
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<tr>
<td>Ground Based precipitation</td>
<td>NCDC, CIMIS, and LADPW</td>
<td>Hourly</td>
<td>54 Stations</td>
</tr>
</tbody>
</table>

The California Irrigation Management Information System (CIMIS) was established in 1982 by the CDWR and the University of California at Davis in order to provide real weather and climate conditions for California's farmers. There are 120 automated CIMIS stations measuring hourly surface solar radiation, temperature, humidity, wind, precipitation, soil temperature, and surface pressure. Using observed meteorological fields over a well-watered soil, the reference ET is estimated at each site. [http://wwwcimis.water.ca.gov/cimis]. In order to estimate agricultural irrigation water needs, ET$_0$ is converted to crop evapotranspiration using a crop coefficient, vegetation type, soil type, and season [Hanson et al. 2004]. Urban landscapes, on the other hand, are composed of collections of vegetation species with different density and microclimates making landscape plantings quite different from agricultural crops. CDWR [2000] utilized
species, density, and microclimate factors to introduce a landscape coefficient to be used instead of crop coefficient in urban landscapes. Based on the authors' knowledge of dominant species in Los Angeles landscapes and a species evaluation report by CDWR [2000], landscapes in the study domain are assumed to have between "Moderate" (trees and shrubs) and "High" (turf grass) water needs (average species factor=0.65) and "average" category for density and microclimate factors (density and microclimate factors =1). Utilizing these factors, in the current analysis, we prescribe a landscape coefficient of 0.65 (landscape coefficient = species factor × density factor × microclimate factor). This coefficient and ET₀ data from six CIMIS stations within close proximity of the study area (Fig. 1) are used to compute urban landscape evapotranspiration which is then employed in evaluation of the Noah-UCM.

2.4. Methods

2.4.1 Noah LSM-UCM Modeling Framework

The single-layer UCM [Kusaka et al. 2001; Kusaka and Kimura 2004] was developed to represent artificial surfaces in LSMS. The UCM models an infinitely-long street canyon and considers the three-dimensional nature of urban surfaces. This scheme includes parameterized street canyons, shadowing of buildings, reflection and trapping of radiation in the canopy, canopy orientation, diurnal variation of solar azimuth angle, canopy flow model [Inoue 1963], multi-layer heat equation for temperature (for roofs, walls, and roads), and a very thin bucket model for hydrological calculations. Prognostic variables include surface temperature and temperature profiles within roof, wall, and road using surface energy budget and thermal conduction equations. The UCM estimates surface sensible heat flux (using Monin-Obukhov similarity theory and the Jurges formula), momentum flux, canyon drag coefficient, and friction
velocity. Anthropogenic Heating (AH) and its diurnal variation are incorporated into the sensible heat flux calculations. The UCM is easily incorporated in mesoscale models without changing the dynamic core and has closely predicted observed surface temperature and net radiation [Kusaka and Kimura 2004]. Moreover, the single-layer parameterization has shown a comparable performance to significantly more complex multi-layer UCM predicting surface fluxes [Kusaka et al. 2001].

Experiments are performed with the UCM implemented within the Noah LSM (version 3.3). The Noah LSM [Chen et al. 1996; Koren et al. 1999] was developed in 1993 by NOAA’s NCEP (National Centers for Environmental Prediction) through a wide collaboration with public and private institutions. Noah is a stand-alone, 1D column model based on a diurnally dependent Penman potential evaporation approach, a multi-layer soil model, a canopy model with a modestly complex canopy resistance scheme, surface hydrology, and snow and sea-ice parameterizations [Chen and Dudhia 2001]. Noah provides prognostic variables including soil ice, moisture, and temperature in different soil layers, stored water in plant canopy, and snow stored on the ground.

The developed modeling framework is adopted over the 49 km² study domain (described above) at a 30 m spatial resolution and at an hourly time step. The Noah LSM is responsible for surface fluxes and temperatures for the vegetated portion of a pixel (e.g. trees, lawns, and parks) and the UCM provides the fluxes for impervious areas. The results are coupled through urban fraction parameter which is defined as the proportion of anthropogenic surfaces in a grid cell.
2.4.2 Irrigation Module Development

Similar to a recent methodology proposed by Pokhrel et al. [2012], which focused on crop irrigation representation within a land surface model, the new anthropogenic soil moisture contribution or irrigation module involves the soil moisture deficit which is the difference between irrigated soil moisture content and actual soil moisture content. Irrigated soil moisture \((\text{SMC}_{\text{IRR}}; \text{m}^3 \text{m}^{-3})\), soil moisture deficit \((\text{DEF}; \text{m}^3 \text{m}^{-3})\), and irrigation water \((\text{IRR}; \text{kg m}^2 \text{s}^{-1})\) are calculated for the natural portion of each grid pixel using:

\[
\text{SMC}_{\text{IRR}} = \alpha \cdot \text{SMC}_{\text{max}} \quad \text{Eq. (1)}
\]

\[
\text{DEF} = \max[(\text{SMC}_{\text{IRR}} - \text{SMC}_1), 0] \quad \text{Eq. (2)}
\]

\[
\text{IRR} = \frac{\rho_w}{\Delta t} \text{DEF} \cdot D_1 \quad \text{Eq. (3)}
\]

Where \(\text{SMC}_{\text{max}} \text{m}^3 \text{m}^{-3}\) is saturation soil moisture content (soil porosity); \(\alpha\) is Irrigation demand factor which is unit less and ranges from zero to one; \(D_1\) represents first soil layer thickness (0.1 m); \(\rho_w \text{ (kg m}^{-3}\) and \(\Delta t\) are water density and model time step (3600 s), respectively. The irrigation module runs within the Noah LSM and updates the top soil layer moisture content \((\text{SMC}_1; \text{m}^3 \text{m}^{-3})\) to the irrigated soil moisture content at a selected interval. In this analysis, irrigation is assumed to be automatic and with no water loss (fully effective) over the current study domain. The parameter \(\alpha\), via irrigated soil moisture content, defines an upper limit for the added soil moisture to the top soil layer to prevent unrealistic heavy irrigation. Previous studies on anthropogenic water in non-urban areas [Hanasaki et al. 2008a, 2008b; Pokhrel et al. 2012] utilized an irrigation demand factor of 1 for rice and 0.75 for other crops. In this work, we prescribe the irrigation demand factor at 0.55, 0.65, 075, 0.85, and 0.95, and test sensitivity of the developed model to this range of \(\alpha\) values. This parameter \((\alpha)\), along with the specified
irrigation interval, characterizes the applied water and is constrained by water consumption records at the monthly scale. Irrigation water is evaluated with several input scenarios: continuously (continuous irrigation), once a day, and every three days (pulse irrigations) to illustrate the impact of irrigation timing on urban water budget and calibrate the simulated irrigation.

2.4.3 Static and Forcing Fields

The Noah-UCM modeling framework requires static data to describe surface characteristics, including soil type, slope type, vegetation type, urban type, and urban fraction (impervious portion of a grid cell). Soil classification information is collected using Soil Data Mart [http://soildatamart.nrcs.usda.gov] and the Los Angeles Department of Public Works (LADPW) data sets. NOAA C-CAP-2006 land cover data is gathered and transformed to urban type, urban fraction, and vegetation type maps. Three out of four developed land cover types recognized by NOAA (developed high, medium, and low intensity) are converted to three UCM urban types (industrial and commercial, high intensity, and low intensity residential) and the developed open space type, along with natural land classes, are categorized as one of 27 Noah LSM vegetation types.

The offline Noah LSM-UCM is forced using ground-based measurements of hourly data, for the period of 1 January 2003 to 31 December 2004, from stations managed by CIMIS, the National Climatic Data Center (NCDC) and LADPW (Table 1). There are six CIMIS, seven NCDC, and 41 LADPW stations inside the Los Angeles metropolitan area (Figure 1). Five NCDC stations are located at smaller regional airports; one is installed at a major airport (Los Angeles International Airport; LAX); and, one is located at a university (University of Southern California; USC) campus, close to the Los Angeles downtown. Since these NCDC sites are
within the Los Angeles metropolitan area, the reported meteorological conditions are assumed to be the representative of the studied urban domain and are utilized for wind speed, air temperature, relative humidity, air pressure, and incoming long wave radiation. The NCDC stations employ Automated Surface Observing Systems (ASOS) and collect data at a standard reference height of 2m. Six regional CIMIS stations are utilized for solar radiation (using LI200S pyranometer which features a high stability silicon photovoltaic detector) and tipping bucket rain gauges in 54 stations (NCDC, CIMIS, and LADPW) are included for estimation of precipitation. Inverse-distance weighting (2\textsuperscript{nd} power) is utilized to create the spatial gridded forcing fields. Missing data are estimated using linear interpolation and the nearest neighbor gage data.

2.4.4. Parameter Estimation

UCM uses numerous parameters to characterize the artificial land-cover fraction of a grid cell. Parameters include thermal properties (e.g., albedo, emissivity, and heat capacity of roof, wall and road), normalized dimensions of canyon geometry (morphological parameters), and anthropogenic heat emission. A brief sensitivity study of Urban Canopy Parameters (UCPs) is undertaken with a focus on surface latent, sensible, ground heat fluxes and land surface temperature. In agreement with Loridan et al. [2010], our analysis indicates that parameters characterizing roof properties are significantly more important than canopy properties. Loridan et al. [2010] also did a comprehensive parameterization of UCM using the Multiobjective Shuffled Complex Evolution Metropolis (MOSCEM) optimization algorithm and field observations in Marseille. Optimum parameter values defining thermal characteristics of artificial surfaces are adopted from this study for the UCM over the Los Angeles area (Table 2). The urban fraction parameter is also updated using the information provided by NOAA C-CAP-2006 land cover data (Table 2). Moreover, to reflect the Los Angeles unique landscape greenness patterns, that
have minimum seasonal variation, the default monthly GVF values are replaced, utilizing weekly
global GVF data provided by NOAA START (the Center for Satellite Applications and
Research; http://www.star.nesdis.noaa.gov/smcd/emb/vci/gvps/gvps_realtimedata.php). The
morphological parameters and parameters corresponding to varying vegetation and soil classes
are kept at their default values, as documented in Chen et al. [2011] and Chen and Dudhia
[2001].

Table 2. Urban canopy parameters adopted using a study by Loridan et al. [2010] and information
provided by NOAA C-CAP.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Industrial and commercial</th>
<th>High intensity residential</th>
<th>Low intensity residential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>default</td>
<td>adopted</td>
<td>default</td>
</tr>
<tr>
<td>Urban fraction</td>
<td>Fraction</td>
<td>0.95</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Heat capacity, roof</td>
<td>J m$^{-3}$ K$^{-1}$</td>
<td>1000000</td>
<td>604674</td>
<td>1000000</td>
</tr>
<tr>
<td>Heat capacity, wall</td>
<td>J m$^{-3}$ K$^{-1}$</td>
<td>1000000</td>
<td>2299510</td>
<td>1000000</td>
</tr>
<tr>
<td>Thermal conductivity, roof</td>
<td>J m$^{-1}$ s$^{-1}$ K$^{-1}$</td>
<td>0.67</td>
<td>0.363</td>
<td>0.67</td>
</tr>
<tr>
<td>Thermal conductivity, wall</td>
<td>J m$^{-1}$ s$^{-1}$ K$^{-1}$</td>
<td>0.67</td>
<td>2.299</td>
<td>0.67</td>
</tr>
<tr>
<td>Surface albedo, roof</td>
<td>Fraction</td>
<td>0.2</td>
<td>0.135</td>
<td>0.2</td>
</tr>
<tr>
<td>Surface albedo, wall</td>
<td>Fraction</td>
<td>0.2</td>
<td>0.052</td>
<td>0.2</td>
</tr>
<tr>
<td>Surface albedo, road</td>
<td>Fraction</td>
<td>0.2</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>Surface emissivity, roof</td>
<td>–</td>
<td>0.9</td>
<td>0.851</td>
<td>0.9</td>
</tr>
<tr>
<td>Surface emissivity, wall</td>
<td>–</td>
<td>0.9</td>
<td>0.98</td>
<td>0.9</td>
</tr>
<tr>
<td>Surface emissivity, road</td>
<td>–</td>
<td>0.95</td>
<td>0.98</td>
<td>0.95</td>
</tr>
</tbody>
</table>

2.4.5. Experimental Design

Various model simulations are undertaken with the Noah-UCM, after incorporating the
developed irrigation scheme over the 49 km$^2$ (7×7km) study domain (Figs. 1 and 2) at the spatial
and temporal resolutions of 30 m and 1 hour, respectively. The integrated model includes an
option to turn the developed irrigation module on or off and control the Irrigation demand factor
($\alpha$). Four experiments are performed to assess the effect of irrigation on surface fluxes and
temperature: control, continuous irrigation, and pulse irrigations at select intervals (every day
and every 3 days). No irrigation was applied in the control experiment. In the continuous irrigation run, soil moisture is kept at the irrigated soil moisture at each time step; more realistically, pulse irrigation modules, assume that lawns and gardens are irrigated at a selected gap and add water once every 24 and 72 hours at 1 am to avoid large solar radiation flux periods. The irrigated soil moisture to which the top soil layer moisture is updated is initially set to 55%, 65%, 75%, 85%, and 95% to assess the sensitivity of meteorological fields to the newly introduced parameter. Next, the irrigation demand factor and irrigation interval are determined using monthly outdoor water use estimates. All experiments use the same forcing fields and parameter set as described in sections 4.3 and 4.4. The study period is 1 January 2003 to 31 December 2004 with the first three months used as model initialization.

Addition of the irrigation model to the Noah-UCM requires alteration of the surface heat exchange coefficient (CH) calculation [based on Chen et al. 1997] in the UCM. The established code uses the same exchange coefficient for both pervious and impervious portions of each cell. Consequently, adding anthropogenic soil moisture to the vegetated part of pixel affects the developed surface emissivity as well. To resolve this issue, the model is altered to calculate exchange coefficient for each land cover type separately.

2.5. Results and Discussion

2.5.1. Sensitivity to Urban Irrigation Rate and Timing

The primary objective of this study is to assess the effects of irrigation on the land surface fluxes (e.g., evapotranspiration and sensible heat flux) and states (e.g., land surface temperature) by developing a realistic irrigation scheme within Noah LSM-UCM modeling framework. Taking the first step toward this objective, we first examine land surface fluxes and temperature
sensitivity to the amount and timing of anthropogenic water added to the revised Noah-UCM. Initially, a once-per-day-pulse irrigation is applied to the vegetated portion of pixels prescribing the demand factor for 0.55, 0.65, 0.75, 0.85, and 0.95 (soil moisture is set to 55%, 65%, 75%, 85%, and 95% of field capacity at a 24 hours interval). Figure 3 shows the latent, sensible, and ground heat fluxes and LST diurnal variations for the entire study area, averaged over the summer months (July, August, and September) in California for both years. For all illustrated variables, sensitivity to the irrigation rate (demand factor) is most substantial at midday. Peak evapotranspiration is increased by 66 W m\(^{-2}\), maximum sensible heat flux is decreased by 76 W m\(^{-2}\), and peak ground heat flux (toward ground) is increased by 15 W m\(^{-2}\) when the irrigation amount is raised from 55% to 95% of soil saturation (Figs. 3a, b, and c).

Figure 3. Diurnal cycles of (a) sensible heat flux, (b) latent heat flux, (c) ground heat flux, and (d) land surface temperature averaged over the study domain and aggregated for the summer seasons (July, August, and September of 2003 and 2004).
Irrigation elevates soil moisture content, enabling evapotranspiration which alters partitioning of energy between latent and sensible heat fluxes. This transforms the energy budget and is a primary driver of the mentioned changes. As a consequence of the energy budget changes, a peak midday LST cooling of almost 2°C is observed with adding 40% more irrigation water (changing demand factor from 0.55 to 0.95) (Fig. 3d). Similar patterns in mean energy partitioning and LST are observed in other seasons (not shown). However, due to the lower temperatures and available energy level and consequently lower amounts of watering, the irrigation effects are slightly less significant.

The monthly time series of hydrologic inflows (precipitation and irrigation water) and outflows (ET and surface and subsurface runoff) over the fully vegetated areas for 2003 and 2004 are presented in Figure 4. Initially, the irrigation demand factor is fixed at 0.75. Four cases, representing different irrigation timing scenarios, are compared: no irrigation (Fig. 4a), continuous irrigation (Fig. 4b), daily-pulse irrigation (Fig. 4c), and 3-day-pulse irrigation (Fig. 4d). Most of the precipitation inflows occur in winter and spring months. The added irrigation water values show strong seasonal variation in all cases and are significantly higher in the continuous irrigation case compared to the pulse approaches (Figs. 4b, c and d). The seasonal cycle of evapotranspiration is also evident in all cases. With no anthropogenic soil moisture available, ET peaks in springtime corresponding to the rainfall period (Fig. 4a). Adding irrigation, ET continues to show high rates in spring months and peaks again in summertime due to high temperatures and available energy level (Figs. 4b, c, and d). Surface runoff stays insignificant, even with irrigation, but subsurface runoff corresponds directly to the irrigation water that is not evaporated. In contrast with 3-day-pulse irrigation (Fig. 4d), continuous and everyday-pulse irrigation (Fig. 4b and c) schemes add so much water to the soil that much of the
excess water is drained as subsurface runoff and is not used in evapotranspiration (energy limited). Changing the pulse irrigation interval from one to three days, confirms that ET, irrigation water, and ground runoff are sensitive to the irrigation timing (Figs. 4c and d).

![Figure 4](image)

Figure 4. Monthly cumulative totals of simulated land surface water budget over fully vegetated areas for (a) no irrigation, (b) continuous irrigation, (c) daily-pulse Irrigation, and (d) 3-day-pulse irrigation for January 2003-December 2004.

### 2.5.2 Irrigation Module Calibration

Using the Noah LSM-UCM and the proposed irrigation scheme, we next quantify the amount and timing of urban irrigation water. Currently, no satisfactory or consistent estimate of urban irrigation is available. Mitchell et al. [2001] noted that garden irrigation practices are extremely variable and assumes a minimum soil moisture level is maintained in irrigated gardens. Jarvi et al., [2011] and Grimmond et al. [1996] relied on a local survey and bi-monthly water bills to estimate outdoor water use. Even in the case of agricultural irrigation, the amount of water to be added to the simulated soil layer is still unresolved [Sorooshian et al. 2011]. In the current study,
different irrigation timing and intensity scenarios are adopted and results are evaluated against
the three outdoor water use estimates. Simulations using continuous, daily, and 3-day pulse
irrigation with demand factor of 0.55, 0.65 and 0.75 are compared with two sets of monthly
outdoor water consumption estimates (Fig. 5). Outdoor water use estimates, based on minimum
and average month methods, show a similar amplitude and cycle. Continuous and every day-
pulse watering rates, using the irrigation demand factor of 0.75, are significantly higher than
outdoor use values. When a 3-day-pulse irrigation scheme is utilized, the Noah LSM-UCM
irrigation water matches the estimated outdoor water use relatively well. Our analysis shows that
increasing the soil moisture to 65% of field capacity with a 3-day watering interval results in
monthly irrigation magnitudes and variations that have the best comparison with the outdoor
water use data (Fig. 5). However, estimated outdoor water use shows a stronger seasonal pattern,
compared to simulated irrigation rates, with the largest water use in summer and near zero values
in the winter. It should be noted that winter outdoor water use estimates are likely too low given
that many homeowners in the Los Angeles region irrigate during the winter months. The Pacific
Institute [2003] indicated that the assumption that the difference between wintertime and other
months of year is equal to outdoor use may not hold in some regions. For instance, in San
Fernando Valley, Johnson and Belitz [2012] observed that landscapes, supported by water
delivery, maintain constant NDVI (Normalized Difference Vegetation Index) throughout the
year, in contrast to common seasonal behavior of greening in the winter/spring and browning in
the summer.
Sensitivity of the Noah LSM-UCM to different irrigation rates and three estimates of outdoor water use for Water Year (WY) 2004 (WY is defined as October 1 of the previous year to September 30 of the designated year) are also evaluated over the residential pixels (Table 3). As noted above, irrigation using a 3-day interval (\( \alpha=0.65 \)) yields comparable irrigation values (281.5 mm yr\(^{-1} \) or 42.6\% of total water use) to the outdoor water use estimates (ranging from 186.3 to 231.4 mm yr\(^{-1} \) or 28.2\% to 35.0\% of total water use). Note that minimum and average month methods likely underestimate outdoor water demands 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, 0.85, and 0.95; watering interval of 2, 4, 5, 6, and 7 days; not presented). After examining the results, and current water restriction policies in the
City (LADWP, personal communication), we advocate that updating the soil moisture to 65% of field capacity (demand factor of 0.65) at a 3-day interval introduces an appropriate amount of irrigation to the system with respect to the outdoor water consumption patterns within the study domain.

Table 3. Comparison of annual Noah LSM-UCM applied water over the residential areas using different irrigation schemes with the three estimates of annual outdoor water use including a CDWR estimate of outdoor water use and "minimum month" and "average month" methods.

<table>
<thead>
<tr>
<th>Irrigation Water Simulations</th>
<th>Rate for WY 2004 (mm/year)</th>
<th>Percentage of Total Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous irrigation (α=0.75)</td>
<td>1311</td>
<td>198</td>
</tr>
<tr>
<td>Pulse irrigation, daily (α=0.75)</td>
<td>725.3</td>
<td>110</td>
</tr>
<tr>
<td>Pulse irrigation, 3-day (α=0.75)</td>
<td>422.7</td>
<td>63.9</td>
</tr>
<tr>
<td>Pulse irrigation, 3-day (α=0.65)</td>
<td>281.5</td>
<td>42.6</td>
</tr>
<tr>
<td>Pulse irrigation, 3-day (α=0.55)</td>
<td>139.9</td>
<td>21.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outdoor Water Use Estimates</th>
<th>Rate for WY 2004 (mm/year)</th>
<th>Percentage of Total Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDWR estimate</td>
<td>231.4</td>
<td>35.0</td>
</tr>
<tr>
<td>“Minimum month”</td>
<td>201.9</td>
<td>30.5</td>
</tr>
<tr>
<td>“Average month”</td>
<td>186.3</td>
<td>28.2</td>
</tr>
</tbody>
</table>

2.5.3 Model Evaluation

Guided by analyses in the previous section, the irrigation demand factor is fixed at 0.65 and irrigation is forced at a 3-day interval (one pulse every 3 days). Next, evapotranspiration and land surface temperature, with and without utilizing the modified irrigation module, are simulated (Figs. 6, 7, 8 and 9). Figure 6 shows the comparison of the simulated ET and LST maps with the remote sensing products, MODIS-Landsat ET product [Kim and Hogue, 2008; 2012; 2013] and Landsat-based LST, for May 4, 2004. Compared to the remote sensing data,
both ET and LST results from the simulation with the established irrigation module show similar spatial patterns. The lower ET rates and higher LST values in the street and road networks are clearly identifiable when the calibrated irrigation module is utilized, in contrast with the no irrigation simulation (Fig. 6a). The highest evapotranspiration rates and lowest skin temperatures are observed in the parks and low intensity residential areas. Results, when the irrigation scheme is integrated into the model, are improved in both ET and LST (Fig. 6a). However, the amount of improvement depends on pixel urban class. Both ET and LST biases are noted before and after adding irrigation (Fig 6b). Overall, the negative ET biases are less significant over the entire study domain after adding irrigation (Fig. 6b). Specifically, ET patterns and values in fully vegetated and low intensity residential pixels are significantly improved (from bias of -81% to -5%). On the other hand, adopting proposed watering scheme, industrial and commercial and high intensity residential evapotranspiration rates are still underestimated in comparison with the MODIS-Landsat based ET (Fig. 6b). It should be noted that the remote sensing ET algorithm shows a slightly high bias for ET, likely given its foundation on radiation-driven ET [Kim and Hogue, 2008; 2012; 2013], and is used here primarily to evaluate spatial patterns in the Noah-UCM based ET relative to another high resolution ET product. The model performance, relative to reproducing the observed LST patterns, is improved when irrigation is considered (Fig. 6b). The positive LST biases for parks and heavily vegetated areas are reduced when the irrigation scheme is incorporated in the model (from 8% to 4%). In highly urbanized regions, the model simulations are also improved but still show negative biases (Fig. 6b). Two possible reasons may explain differences between the two estimates. One reason may be that Noah LSM-UCM utilizes land cover based albedo and emissivity values (look up tables), which may introduce significant uncertainty in the results. Another reason may be not including anthropogenic heating in the
present model analysis, due to the lack of adequate data. Several studies [Taha 1999; Taha and Ching 2007; Miao et al. 2009a; Chen et al. 2011] demonstrated the significant impact of anthropogenic heating on urban temperatures.

Figure 6. (a) Simulated ET and LST maps, before (left) and after adding irrigation (middle), with MODIS-Landsat products (right). (b) Spatial differences between simulated and remotely sensed ET and LST, before (left) and after adding irrigation (right). All the images are valid at 1125 (local time), May 4, 2004.
To more fully examine the developed modeling framework, the diurnal variability of simulated ET and LST over fully vegetated areas, with and without inclusion of the developed irrigation scheme, are highlighted (Fig. 7). MODIS-Landsat-based ET, CIMIS based ET, and Landsat-based LST observations are also indicated. We present comparisons only for the days with a usable Landsat overpass product with minimal missing data to minimize uncertainties. In general, model simulations with the irrigation module reproduce ET rates that are much closer to the remotely sensed values when compared to simulations with no irrigation (Fig. 7a). As expected, runs with no irrigation underestimate ET rates significantly and consistently. This is confirmed when simulated ET and hourly ET measurements from CIMIS stations are compared (Fig. 7a). Significant negative biases, noted in the no irrigation case, are reduced by adding irrigation water to the system (RMSE is decreased from 77.11 to 25.05 W m$^{-2}$). These results highlight that the variations of ET are greatly improved at the daily time scale by the introduction of irrigation (Fig. 7a). Simulations with the developed irrigation scheme show LSTs that are close to the Landsat values for most days (Fig. 7b). The increase in ET also leads to a decrease in LST (Fig. 7a and b). Sorooshian et al. [2011] also reported a 4-5 °C decrease in skin temperature adding agricultural irrigation in California's Central Valley. However, our results indicate irrigation results in a cooling bias of about 2 °C in urban parks (averaged over Landsat overpass days; Fig. 7b). Further comparison of Noah LSM-UCM-simulated ET and LST values with concurrent remotely sensed data is also presented (Fig. 8). As observed, the correlation between simulated ETs and measured values is significantly increased ($R^2$ is increased from 0.03 to 0.57) and the biases are decreased (RMSE is decreased from 169.5 to 48.82 W m$^{-2}$) when irrigation is added to the system. This confirms the significance role of irrigation in the model ability to simulate urban ET fields. The agreement between simulated surface temperatures and concurrent
observations is also enhanced ($R^2$ is increased from 0.73 to 0.83; RMSE is decreased from 3.529 to 2.546 °C) with the introduction of irrigation to the model.

Figure 7. Diurnal cycles for Landsat overpass days that include simulated ET (a) and LST (b), before and after adding irrigation, and their comparisons with MODIS-Landsat products (open circles) at Landsat overpass time (1125 local time). The concurrent CIMIS based hourly ET measurements are also indicated (a).
Figure 8. Comparison of Noah-UCM-predicted ET and LST to the remotely sensed values, before and after adding irrigation. Each dot represents an average value over the entire study domain concurrent with each Landsat overpass.

In addition to the remote sensing-based ET and LST products, CIMIS data is also used to evaluate model performance (Fig. 9). Generally, the CIMIS-based ET values from the selected stations show similar monthly rates and seasonal variations, and model simulations with the irrigation module compare well with these values (Fig. 9). In contrast, the non-irrigation simulation produces strong biases in ET. When compared to the interpolated CIMIS based ET, the non-irrigation simulation underestimates ET rates, most significantly during the summer months, while the irrigation simulation gives reasonable predictions of the CIMIS based ET. The evapotranspiration errors for the non-irrigation simulation are -56 and -90 mm/month for July 2003 and 2004, respectively, while these values reduce to -6 and -11 mm/month over the same two months when the irrigation scheme is adopted (Fig. 9). Our results are consistent with the water balance study conducted by Mitchel et al. [2008] which reported the effects of irrigation on
ET to be most significant in summer months and illustrated that without irrigation, rainfall cannot meet the evaporative demands of an urban setup.

Figure 9. Monthly cumulative totals of simulated ET over fully vegetated areas, before and after adding irrigation, with the CIMIS-based ET values (from different stations) for January 2003-December 2004. The interpolated CIMIS based ET are also indicated.

2.5.4. Impact of Irrigation on Water Balance

Precipitation, irrigation water, ET, and surface and subsurface runoff results obtained for two simulations, i.e. non-irrigation and irrigation, are compared for different land cover types as well as over the study domain for WY 2004 (Table 4). The study area received a total of about 257 mm of rainfall during WY 2004 which is about 100 mm less than the historical thirty-year average [1949 to 2006; Western Regional Climate Center, http://www.wrcc.dri.edu]. Across land cover classes, irrigation water ranges from 607.4 to 60.13 mm/year. The highest/lowest applied water volume corresponds to the highest/lowest vegetation fraction, which is at a maximum over fully vegetated pixels (100%) and at a minimum over industrial and commercial regions (10%).
When compared to the non-irrigation simulation, the Noah LSM-UCM with irrigation produces much higher ET rates across the study domain; the evapotranspiration for WY 2004 is 748.5 mm/year for grass, 671.5 and 295.7 mm/year for low and high intensity residential, 84.92 mm/year for industrial and commercial, and 260.7 mm/year for the entire study area. As expected, surface runoff is lowest for fully vegetated surfaces and highest for industrial and commercial. The irrigation-induced surface runoff variations are not remarkable due to the fact that significant surface runoff rates already occur over highly impervious lands, and minimal irrigation water is also applied for these areas. However, the irrigation-induced subsurface recharges are significant for more pervious surfaces, ranging from 137.6 mm/year for parks to 5.231 mm/year for heavily urbanized areas. A 607.4 mm increase in annual hydrological inflow over fully vegetated areas corresponds to a 477.5 and 125.4 mm increase in ET and groundwater recharge, respectively. In other words, over grassy areas, about 79% and 21% of extra water added to the surface is lost to evapotranspiration and subsurface runoff, respectively. These values scale to 83% and 9.3% for the entire study area.

Table 4. Simulated annual water budgets, before (No IRR) and after adding irrigation (IRR), over different land cover types as well as over the study area for WY 2004 (mm/year).

<table>
<thead>
<tr>
<th></th>
<th>Fully Vegetated</th>
<th>Low Int. Res.</th>
<th>High Int. Res.</th>
<th>Indus. &amp; Comm.</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No IRR</td>
<td>IRR</td>
<td>No IRR</td>
<td>IRR</td>
<td>No IRR</td>
</tr>
<tr>
<td>Precipitation</td>
<td>257.2</td>
<td>257.2</td>
<td>258.6</td>
<td>258.6</td>
<td>258.8</td>
</tr>
<tr>
<td>Irrigation water</td>
<td>0.0</td>
<td>607.4</td>
<td>0.0</td>
<td>475.5</td>
<td>0.0</td>
</tr>
<tr>
<td>ET</td>
<td>271.0</td>
<td>748.5</td>
<td>280.1</td>
<td>671.5</td>
<td>122.9</td>
</tr>
<tr>
<td>Surface Runoff</td>
<td>7.221</td>
<td>11.44</td>
<td>56.43</td>
<td>58.91</td>
<td>170.3</td>
</tr>
<tr>
<td>Subsurface Runoff</td>
<td>12.21</td>
<td>137.6</td>
<td>0.0</td>
<td>48.14</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Liu et al. [2011] performed a long-term water balance on the Ballona Creek watershed in the greater Los Angeles, which includes the current study domain. For WY 2004, a runoff depth of 189 mm was observed for the watershed. This estimate agrees well with our results showing a surface runoff of ~183 mm over the same period. We further evaluate the simulated water budget by comparison to recent ET measurements in the Los Angeles area [Moering 2011]. Moering [2011] employed a previously developed chamber method to measure instantaneous ET in an irrigated and a non-irrigated park in the greater Los Angeles area during WY 2011. They reported an annual evapotranspiration of about 1200 mm over irrigated parks. This value cannot be directly compared with our results since these ET measurements were carried out during a wetter, and different, water year. For 2011, they reported an annual precipitation amount of 556 mm, which is more than twice what our study domain received during WY 2004. However, during WY 2011, they reported the measured ETs to be about 66% of CIMIS recorded reference ET rates. For the current study, 66% of CIMIS-based $ET_0$ is equal to 814 mm for WY 2004, which compares reasonably well with the simulated grass ET of ~749 mm/year. Based upon these similarities, we advocate that the Noah LSM-UCM with the proposed irrigation scheme is capable of estimating the surface meteorological features with reasonable accuracy. The irrigation scheme enables the simulated ET to approximate the observations with an overall bias of 8.0% for WY 2004.

2.6. Conclusions

The current study develops, incorporates and systematically evaluates an irrigation scheme within the Noah LSM-UCM framework. The goal is not only to use the developed irrigation module to improve Noah LSM-UCM capabilities and thereby enhance WRF weather forecasts over arid and semi-arid urban areas, but also to establish a modeling tool for assessing the
impacts of irrigation on urban meteorological fields. The developed modeling framework is applied over a 49.0 km² study area in the Los Angeles metropolitan area at a high resolution to better understand the temporal variability and spatial heterogeneity of urban water fluxes in this region. 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 budget, hydrological fluxes and state variables. When evaluated against the LADWP residential records and the monthly outdoor water use data, the proposed irrigation scheme with an irrigation demand factor of 0.65 and irrigation interval of 3 days (one pulse every 3 days), reasonably represents irrigation fluxes over the study region.

When compared to the instantaneous MODIS-Landsat ET product as well as the hourly CIMIS-based landscape ET observations, modeling results in the Los Angeles region indicate that the Noah LSM-UCM can simulate ET patterns at daily and monthly scales, when a reasonable irrigation module is incorporated. However, without irrigation, the model produces large biases in ET simulations, supporting our hypothesis that addition of an irrigation module is critical to adequately simulate the hydrologic cycle in the Los Angeles domain. The LST biases for parks and heavily vegetated areas, compared to the instantaneous Landsat LST product, are also reduced when the irrigation scheme is integrated in the model. In highly urbanized regions, on the other hand, the model simulations still show negative biases. Errors in the LST predictions over the heavily urbanized regions are likely due to the lack of anthropogenic heating representation in the current analysis. Our speculation is that the albedo and emissivity values used by the model, which involves land-cover maps and corresponding parameter look-up tables, may have contributed to these uncertainties. In close agreement with previous modeling based
research [Sorooshian et al. 2011], our results show a 2 °C decrease in land surface temperature with the addition of irrigation in urban parks.

Using the modified irrigation module, the surface energy budget components for WY 2004 are reproduced. Based upon the agreement between our results and recent studies [Liu et al. 2011; Moering 2011], we are confident that the Noah LSM-UCM with the proposed irrigation scheme is capable of estimating the surface meteorological features with reasonable accuracy at the annual scale. Our results also indicate that most of the irrigation water is lost through evapotranspiration and subsurface drainage. In other words, 83% and 9.3% of the extra (irrigated) water added to the study area is lost to evapotranspiration and subsurface runoff, respectively.

This work advances beyond previous studies by integrating the urban LSM framework with a sophisticated irrigation scheme that can account for the essential role of anthropogenic water contribution in urban hydrologic cycles. The developed modeling system is a useful tool for quantifying urban water fluxes, particularly in arid and semi-arid regions where imported water significantly impacts the local urban water budgets through landscape application. The validated model is being utilized for a number of potential applications, ranging from local water use estimation to climate change impact assessments.

Ongoing work is focused on more accurate definition of urban canopy parameters, such as albedo, emissivity, and anthropogenic heat flux. The traditional approach (look-up tables based on land-cover type) appears limited for heavily urbanized and heterogeneous areas (i.e. "high intensity residential" and "industrial and commercial" areas). We advocate that remote sensing-based products (satellite and tower data) are a promising source for model parameters. We also
note that further research quantifying the impacts of irrigation on energy and water cycles is needed over broader urban domains. The developed urban modeling framework will ultimately be used over water scarce metropolitan areas (e.g. Los Angeles, California and Las Vegas, Nevada) under different climate and land use change scenarios to help with current and future water management challenges and decision making processes.

Acknowledgements

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Chapter 3. High Resolution Land Surface Modeling Utilizing Remote Sensing Parameters and the Noah-UCM: A Case Study in the Los Angeles Basin

3.1. Introduction

Urbanization introduces significant changes to land surface characteristics that ultimately perturb land-atmosphere fluxes of sensible heat, latent heat, and momentum which, in turn, alter atmospheric properties as well as local weather and climate [Miao et al., 2009; Ridder et al., 2012; Kalnay and Cai, 2003; Landsberg, 1981]. Urban surfaces are covered with variety of materials with distinct thermal, radiative, and moisture properties influencing surface energy and water budgets [Arnfield, 2003]. Moreover, contrasting aerodynamic properties of buildings significantly change surface roughness [Cotton & Pielke, 1995]. The effects associated with modified urban landscapes extend to air quality [Taha et al., 1997], local temperatures [Van Wevenberg et al., 2008; Bornstein, 1987], local and regional atmospheric circulation [Pielke et al., 2002; Marshall et al., 2004; Niyogi et al., 2006], and regional precipitation patterns [Changnon and Huff, 1986; Changnon, 1992; Lowry, 1998].

Mesoscale meteorological models have been increasingly applied over urban areas to examine the urban-atmosphere exchange of heat, moisture, momentum or pollutants. Recently updated parameterization in the community Weather Research and Forecasting (WRF) model includes coupling between the Noah LSM and a single layer UCM [Kusaka et al. 2001; Kusaka and Kimura, 2004] which has substantially advanced the understanding and modeling of the mesoscale impact of cities. The coupled WRF-Noah-UCM has been applied to major metropolitan regions around the world (e.g. Houston, Beijing, Guangzhou/Hong Kong, Salt Lake City, and Athens) to better understand the contribution of urbanization to changes in urban
heat island, surface ozone, horizontal convective rolls, boundary layer structure, contaminant transport and dispersion, and heat wave events [Chen et al., 2004; Jiang et al., 2008; Miao and Chen, 2008; Miao et al., 2009; Wang et al., 2009; Tewari et al., 2010; Wei-guang et al., 2011; Giannaros et al., 2013]. A common concern with the use of these complex mesoscale models, however, is the high level of uncertainty in the specification of surface cover and geometric parameters [Loridan et al., 2010; Chen et al., 2011]. Although realistic representation of surface properties is critical for accurate simulation of the physical processes occurring in urban regions, the majority of previous modeling studies rely on traditional land-use data and lookup tables to define surface parameters.

Remote sensed observations provide important spatial information on urban-induced physical modifications to the Earth’s surface [Jin and Shepherd, 2005]. Airborne LIDAR (Light Detection and Ranging) systems and photogrammetric techniques have been utilized to produce morphological parameters over urban areas [Burian et al., 2004, 2006, 2007; Taha, 2008; Ching et al., 2009]. Burian et al. [2004] used airborne LIDAR data, at 1 m resolution, to generate datasets of 20 urban canopy parameters (e.g., building height, height-to-width ratio, and roughness length) for an air quality modeling study over Houston, Texas. Tahah [2008] introduced an alternative and low-cost approach for generating urban canopy parameters input for the uMM5 over Sacramento region, California. The study relied on commercially available Google Earth PRO imagery to generate urban geometry parameters (e.g., pavement land-cover fraction, roof cover fraction, and mean building height). Using LIDAR based three-dimensional data sets of buildings and vegetation, Ching et al. [2009] presented a high-resolution database of the geometry, density, material, and roughness properties of the morphological features for applications in WRF and other models over Houston, Texas. While promising, the availability of
such datasets is currently limited to a few geographical locations and the reproduction of such
datasets is extremely challenging due to high collection costs and data management difficulties
associated with the extremely large size of LIDAR datasets [Ching et al., 2009; Burian et al.,
2006].

Observations from satellites, on the other hand, have been utilized in model validation processes
over urban areas [Giannaros et al, 2013; Miao et al., 2009]. In addition to in situ observations,
Giannaros et al. [2013] included MODIS based LST products in their modeling study of the
urban heat island over Athens, Greece. Similarly, Miao et al. [2009] utilized 1-km-resolution
MODIS data to verify the WRF-Noah-UCM simulated LST distribution in Beijing. Other studies
have employed satellite data to replace outdated urban land use maps in atmospheric models with
new remote sensing products [Cheng and Byun, 2008; Cheng et al., 2013]. Focusing on
boundary later mixing conditions and local wind patterns in the Houston Ship channel, Cheng
and Byun [2008] reported that the Noah LSM and planetary boundary layer (PBL) scheme
performances in the MM5 were improved when land-use type distributions were correctly
represented in the model using high resolution Landsat based land use data. Cheng et al. [2013]
compared WRF simulations in the Taiwan area using U.S. Geological Survey (USGS), MODIS,
and SPOT (Système Pour l’Observation de la Terre) based land use data. Using the new high
resolution land use types obtained from SPOT satellite imagery, the WRF perditions of daytime
temperatures and onshore sea breezes had the best agreement with observed data. Furthermore,
more accurate surface wind speeds were simulated when MODIS and SPOT data replaced
conventional USGS land use maps in the WRF runs due to the more realistic representation of
roughness length in the remotely sensed databases. Although these and other previous studies
[e.g., Jin and Shepherd, 2005] have recognized the usefulness of satellite imagery (e.g., NASA’s
Terra, Aqua, and Landsat data) in specifying surface physical characteristics in urban environments, very few have directly incorporated high resolution gridded satellite based parameters (e.g., impervious surface area, albedo, and emissivity) into parameter estimation within land surface/atmospheric modeling systems.

In the current work we investigate the utility of remote sensing based surface parameters in the Noah-UCM modeling framework over a highly developed urban area. Among parameters that can be related to a measurable physical quantity, we evaluate those routinely and freely obtained from satellite-based platforms. The derived parameter sets are implemented in the Noah-UCM with a focus on simulated surface energy and water cycles that are essential feedback to the widely used WRF model. Landsat and fused Landsat-MODIS data are utilized to generate high resolution (30 m) monthly spatial maps of green vegetation fraction (GVF), impervious surface area (ISA), albedo, leaf area index (LAI), and emissivity in the Los Angeles metropolitan area. The temporal and spatial distributions of newly assigned parameters are compared with those based on the model lookup tables. Next, gridded remotely sensed parameter datasets are directly incorporated into the Noah-UCM modeling framework replacing the land-use/lookup table based values. The sensitivity of the simulated energy and water fluxes to the newly developed spatial metrics of parameters is presented. The model's performance in reproducing ET and LST fields is evaluated utilizing Landsat based land surface temperature and ET estimates from CIMIS stations as well as in-situ measurements. Finally, the influence of each parameter set on the urban energy and water budgets is investigated.
3.2. Study Area

The study domain is a 49 km$^2$ highly developed neighborhood in the City of Los Angeles (Fig. 1). Los Angeles is the second most populous city in the United States with a population of 3.8 million [U.S. Census, 2011], covering an area of 1,215 km$^2$ in Southern California. The City has a Mediterranean climate and receives 381 mm of annual precipitation, mostly over the winter months [NOAA-CSC, 2003; SCDWR, 2009]. Due to the semi-arid nature of the region, the City’s water supply is heavily dependent on imported water (52% from the Colorado River and 36% from the Los Angeles Aqueduct) [LADWP, 2010].

![Figure 7](image_url)

Figure 7. (a) NOAA C-CAP Land cover map of the Los Angeles metropolitan area including study domain, 10 CIMIS stations (white circles), and 8 NCDC stations (white squares), (b) Google image of the study domain, and (c) The Noah/UCM urban land cover classification of the study domain.
Regional water demands and the extensive dependence on external sources make accurate spatial representation of the metropolitan area in regional land surface/atmospheric models imperative for predicting current and future water budgets. The study domain includes commercial/industrial as well as low and high intensity residential land cover types and a large park with both irrigated and non-irrigated landscapes (Fig. 1b and 1c).

3.3. Remotely Sensed Parameters

Remote sensing data are retrieved from Landsat ETM+ images with a nominal pixel resolution of 30 m in the short wave bands and 60 m in the thermal band. The level 1Gt ETM+ imagery from USGS EROS, spanning years 2010-2011, are calibrated and atmospherically corrected through the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). Study domain data are not affected by the failure of the Landsat-7 ETM+ Scan Line Corrector in 2033 (SLC-off). Employing a knowledge based approach, similar to the one introduced by Song and Civco [2002], several binary masks are applied to the images to detect contaminated areas (cloud and shadow). Images with cloud and/or shadow are distinguished and omitted in the following parameter retrievals. A total of 24 pure images, acquired over two years, are utilized in the parameter estimation processes.

In addition to Landsat observations, MODIS products from Terra and Aqua satellite platforms are also utilized. The MODIS MCD43A BRDF (Bidirectional Reflectance Distribution Function) products, concurrent with pure Landsat images, are collected for use in the parameter calculations. The 500-m BRDF products are generated by the MODIS Adaptive Processing System (MODAPS) at the Goddard Space Flight Center (GSFC), using a kernel-driven linear model, and distributed through the Land Processes DAAC (Distributed Active Archive Center).
The described Landsat and MOIDS based data are used to produce a group of six remotely sensed derivatives:

**Green Vegetation Fraction (GVF):** GVF spatial maps are derived according to Gutman and Ignatov [1998] utilizing NDVI (Normalized Difference Vegetation Index) measurements. First, atmospheric corrected reflectance values from the red (ρ_{ETM3}) and near-infrared (ρ_{ETM4}) bands of Landsat ETM+ are used to derive NDVI maps for each date of imagery based on Eq. 1. Next, assuming the vegetated part of a pixel is covered by dense vegetations (i.e., it has a high LAI), GVF is calculated using Eq. 2.

\[
NDVI = \frac{\rho_{ETM4} - \rho_{ETM3}}{\rho_{ETM4} + \rho_{ETM3}} \quad \text{Eq. (1)}
\]

\[
GVF = \frac{NDVI_0 - NDVI}{NDVI_{\infty} - NDVI_0} \quad \text{Eq. (2)}
\]

Where NDVI_0 and NDVI_{\infty} are constant values computed using signals from bare soil and densely vegetated pixels in the study domain, respectively.

**Impervious Surface Area (ISA):** ISA is shown to be inversely proportional to vegetation fraction where non-vegetated pervious surfaces are rare [Bauer et al., 2007]. Since the majority of pervious surfaces in the studied domain are vegetated and heavily irrigated throughout the year, ISA is assumed to be the complement of the vegetation fraction:

\[
ISA = (1 - GVF_{\text{max}}) \times 100 \quad \text{Eq. (3)}
\]

Where GVF_{\text{max}} is the maximum GVF detected over the two year study period. The produced ISA map shows high accuracy (>95%) when compared to a previously developed high resolution land cover map, based on QuickBird remote sensing data, aerial photographs, and geographic information systems over the city of Los Angeles [McPherson et al., 2008].
**Albedo:** Employing a recent methodology by Shuai et al. [2011], 30 m land surface albedo maps is generated utilizing Landsat surface reflectance and anisotropy information from concurrent 500 m MODIS BRDF products. Landsat data are reprojected from UTM to MODIS sinusoidal projection and aggregated from 30 m to 500 m. Using USGS based land cover types, the percentage of each land cover class within each MODIS pixel is computed, then relatively pure pixels (>85% purity) are selected for each class. MCD43A2 quality assessment product is used to choose highest quality MODIS MCD43A1 BRDF parameters for the pure pixels. The concurrent parameters are used to calculate nadir reflectance, white sky albedo, and black sky albedo under the solar geometry at Landsat overpass time and MODIS scale. Next, the spectral albedo-to-nadir reflectance ratios, for white sky and black sky albedos, are calculated over the pure pixels. The resultant ratios, specific to each land cover class, are applied to Landsat surface reflectance to generate the spectral white sky and black sky albedos for each Landsat pixel. A further narrowband-to-broadband conversion based on extensive radiative transfer simulations by Liang [2000] is applied to generate the broadband albedos at shortwave regime. Finally, albedo (blue sky) is modeled as an interpolation between the black sky (\( \alpha_{b\,b} \)) and white sky (\( \alpha_{w\,s} \)) albedos as a function of the fraction of diffuse skylight (\( S(\theta, \tau(\lambda)) \)) which is estimated by the 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) codebase (Eq. 4) [Schaaf et al., 2002].

\[
\alpha(\theta, \lambda) = \left[ 1 - S(\theta, \tau(\lambda)) \right] \alpha_{b\,b}(\theta, \lambda) + S(\theta, \tau(\lambda)) \alpha_{w\,s}(\theta, \lambda) \quad \text{Eq. (4)}
\]

where \( \tau, \theta, \) and \( \lambda \) are optical depth, solar zenith, and wavelength, respectively.

**Leaf Area Index (LAI):** Stenberg et al. [2004] showed that a reduced simple ratio (RSR) explains 63%-75% of the variations in LAI and that maps of projected LAI, based on RSR, have good agreement with observations. In the current study, LAI values are retrieved based on the LAI-
RSR correlations which are specified utilizing table based LAI estimates in pure (fully vegetated) pixels and remotely sensed RSR maps. The atmospheric corrected reflectance values of Landsat ETM spectral channels red ($\rho_{ETM3}$), near infrared ($\rho_{ETM4}$), and mid infrared ($\rho_{ETM5}$), implemented in the following equation (Eq. 5), define RSR:

$$RSR = \frac{\rho_{ETM4}}{\rho_{ETM3}} \frac{\rho_{ETM5max} - \rho_{ETM5min}}{\rho_{ETM5max} + \rho_{ETM5min}}$$

where $\rho_{ETM5min}$ and $\rho_{ETM5max}$ are the smallest and largest mid infrared reflectance detected in the Landsat ETM images over the study domain, excluding open water pixels.

**Emissivity:** Among various methods developed to define land surface emissivity, the NDVI Thresholds Method (NDVI$^{THM}$) has been widely applied to urban areas [Tan and Li, 2013; Stathopoulou and Cartalis, 2007; Stathopoulou et al., 2007]. NDVI$^{THM}$ is superior to other methods since the consideration of the internal reflections (cavity effects), caused by heterogeneous surfaces minimizes the overall error in this approach [Sobrino et al., 2001]. This methodology, originally introduced by Sobrino and Raissouni [2000] and modified later by Stathopoulou et al. [2007] for urban areas, is selected for land surface emissivity estimation in the current work. Using the Landsat based NDVI thresholds, the study area is divided into four classes: (1) fully vegetated (NDVI$>$0.5), (2) built-up areas with sparse vegetation (NDVI$\leq$0.2), (3) mixture of man-made material and vegetation (NDVI$>$0.2 and $\leq$0.5), and (4) water bodies (NDVI$<$0). Mean emissivity values of 0.980, 0.920, and 0.995 are then used for fully vegetated, built-up and water pixels [Similar to Tan and Li, 2013]. Emissivity values ($\varepsilon$) for mixed pixels (class 3) are estimated using the following equations [for details see Stathopoulou et al., 2007]:

$$\varepsilon = 0.017P_V + 0.963$$

Eq. (6)
\[ P_V = \frac{(NDVI-0.2)^2}{(0.5-0.2)^2} \quad \text{Eq. (7)} \]

Land Surface Temperature (LST): The emissivity corrected land surface temperature (LST) is calculated as follows [Artis & Carnahan, 1982]:

\[ LST = \frac{BT}{\left( 1 + \frac{LBT}{\rho \cdot \ln \epsilon} \right)} \quad \text{Eq. (8)} \]

where BT is Landsat at sensor brightness temperature (K); \( \lambda \) and \( \epsilon \) are the wavelength of emitted radiance (11.5 \( \mu \)m) and surface emissivity; \( \rho = hc/\sigma \) (1.438 \( \times \) 10\(^{-2}\) m K); \( \sigma \), \( h \), and \( c \) are Boltzmann constant, Planck’s constant, and the velocity of light, respectively.

### 3.4. Numerical Modeling System

#### 3.4.1. Noah LSM-UCM Model

Land surface processes are parameterized using the offline Noah LSM [Chen and Dudhia, 2001] coupled with the single layer UCM [Kusaka et al. 2001; Kusaka and Kimura, 2004]. The Noah LSM is based on a diurnally dependant Penman potential evaporation approach, a multi-layer soil parameterization, a canopy resistance model, surface hydrology, and frozen ground physics [Chen et al., 1996, 1997; Chen and Dudhia, 2001; Ek et al., 2003]. The UCM parameterization includes urban building geometry, shadowing from buildings, reflections and trapping of radiation in a street canyon, and an exponential wind profile. The Noah LSM provides surface sensible and latent heat fluxes and surface skin temperature for vegetated areas (e.g., parks and trees) and the UCM calculates the fluxes for impervious surfaces. The outputs from the Noah LSM and UCM are coupled through the urban surface fractions.
3.4.2. Irrigation Module

Irrigation is accounted for, in the Noah-UCM modeling framework, by incorporating an urban irrigation module developed in our previous work [Vahmani and Hogue, 2013; 2014]. The developed irrigation scheme mimics the effects of urban irrigation by increasing soil moisture content in vegetated portion of grid pixels at a selected interval. Added anthropogenic soil moisture contribution is a function of the soil moisture deficit, which is the difference between irrigated soil moisture content and actual soil moisture content in the top soil layer. The irrigation module calculates irrigated soil moisture content (SMC$_{IRR}$; m$^3$ m$^{-3}$), soil moisture deficit (DEF; m$^3$ m$^{-3}$), and irrigation water (IRR; kg m$^2$ s$^{-1}$) as:

\[
SMC_{IRR} = \alpha SMC_{\text{max}} \quad \text{Eq. (9)}
\]

\[
DEF = \max \{[SMC_{IRR} - SMC_1], 0\} \quad \text{Eq. (10)}
\]

\[
IRR = \frac{\rho_w}{\Delta t} DEF \cdot D_1 \quad \text{Eq. (11)}
\]

where saturation soil moisture content (SMC$_{\text{max}}$; m$^3$ m$^{-3}$) and irrigation demand factor ($\alpha$; unit less) define irrigated soil moisture content (Eq. 9); $D_1$ is top soil layer thickness (10 cm); $\rho_w$ (kg m$^{-3}$) and $\Delta t$ stand for water density and Noah-UCM time step (3600 s), respectively. The parameter $\alpha$, ranging from zero to one, regulates the amount of irrigation water added to the soil each time the scheme increases the soil moisture, simulating an irrigation event. Similar to previous studies [Hanasaki et al. 2008a, 2008b; Pokhrel et al. 2012] an irrigation demand factor of 0.75 is utilized in the current work. The irrigation interval is set to three times per week according to the water restrictions implemented by Los Angeles Department of Water and Power (LADWP) in 2010 (LADWP, personal communication).
3.4.3. Land Cover Data and Forcing Fields

The Noah-UCM modeling system requires static data to describe physical characteristics of the surface, including soil type, slope type, vegetation type, and urban type. A combination of the Soil Data Mart [http://soildatamart.nrcs.usda.gov] and the Los Angeles Department of Public Works (LADPW) databases are used to gather soil classification information. Land use and land cover are parameterized using the 30 m NOAA C-CAP-2006 land cover data which is transformed to urban and vegetation type spatial maps over the study domain. High, medium, and low intensity developed land cover types, recognized by NOAA, are converted to UCM Industrial/Commercial, high and low intensity residential types, respectively. The developed open space along with natural land types are categorized as one of the 27 Noah LSM vegetation classes.

The offline Noah LSM-UCM is forced utilizing hourly ground based observations from CIMIS and National Climatic Data Center (NCDC) stations for the period from 1 January 2010 to 31 December 2011. There are ten CIMIS and eight NCDC stations within close proximity of the study domain (Figure 1a). The NCDC stations, which use Automated Surface Observing Systems (ASOS), are located at smaller local airports (6 stations), one major airport (Los Angeles International Airport), and a university campus (University of Southern California; USC) within the Los Angeles metropolitan area. Reporting the meteorological conditions, the NCDC stations are used for wind speed, air temperature, relative humidity, air pressure, and incoming long wave radiation. All NCDC data are gathered at a standard reference height of 2m. The regional CIMIS stations are utilized for solar radiation (using LI200S pyranometer) and tipping bucket rain gauges in 18 stations (NCDC and CIMIS) are included in collection of precipitation data. Inverse-distance weighting (2nd power) is employed to create the spatial
gridded forcing fields. Linear interpolation and data from the nearest gage are utilized to replace missing data.

3.5. Numerical Experiments and Evaluation Methods

3.5.1. Remote Sensing Based Parameterization

To investigate the sensitivity of the Noah-UCM model to integration of the developed remotely sensed parameters, nine simulation scenarios are designed (Table 1). A control experiment (Scenario 1) is conducted in which all default parameters are utilized in the Noah-UCM. Scenarios 2 to 6 explicitly assess each individual parameter effects on urban energy and water budgets using the newly incorporated remote sensing parameters. Scenario 7 analyzes the effects of employing both remotely sensed GVF and ISA while Scenario 8 assesses simultaneous integration of albedo, LAI, and emissivity. We are interested in the comparison of Scenarios 7 and 8 as the Noah-UCM parameterizations use GVF and ISA to select albedo, LAI, emissivity, and roughness length values from the predefined ranges in the parameter tables. These simulations help quantify the contribution of each parameter group to the model’s ability to reproduce the observed surface states and fluxes. Finally, the last experiment (Scenario 9) implements all five remotely sensed parameter sets in the simulations. It should be noted that the GVF and LAI measurements over mixed pixels (vegetated urban areas) are scaled up using urban fractions since, in the Noah-UCM modeling framework, these parameters characterize only the pervious portion (1 - urban fraction) of each pixel. Other than the implemented remote sending based parameters, the rest of the model parameters are kept at default values. All experiments incorporate the irrigation module and irrigation rates are kept constant in all scenarios. All
scenarios are run at 30 m spatial and 1 hour temporal resolutions, spanning 2010 and 2011, with the first three months used as model initialization.

Table 1. Model scenarios (1-9) and the incorporated remotely sensed parameter sets.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GVF</th>
<th>ISA</th>
<th>Albedo</th>
<th>LAI</th>
<th>Emissivity</th>
</tr>
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<tbody>
<tr>
<td>1 (Def. Par.)</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>2 (R.S. GVF)</td>
<td>X</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>3 (R.S. ISA)</td>
<td>-</td>
<td>X</td>
<td>-</td>
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<tr>
<td>4 (R.S. Albedo)</td>
<td>-</td>
<td>-</td>
<td>X</td>
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<tr>
<td>5 (R.S. LAI)</td>
<td>-</td>
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<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>6 (R.S. Emissivity)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>7 (R.S. Par. Group 1)</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8 (R.S. Par. Group 2)</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9 (R.S. Par. All)</td>
<td>X</td>
<td>X</td>
<td>X</td>
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3.5.2. Model Evaluation Approach

In order to evaluate the performance of the Noah-UCM modeling framework, simulated LSTs are compared with concurrent Landsat observations and simulated latent heat flux time series are assessed against CIMIS based ET observations. The CIMIS network was established in 1982 by the CDWR (California Department of Water Resources) and the University of California at Davis in order to provide real-time weather conditions and irrigation water need estimates for California's agricultural community. The automated CIMIS stations measure hourly surface solar radiation, temperature, humidity, wind, precipitation, soil temperature, and surface pressure [http://wwwcimis.water.ca.gov/cimis]. Employing observed meteorological fields over a well-watered soil, the reference ET (ET<sub>0</sub>) is calculated for each site. Utilizing a methodology introduced by CDWR [2000], actual urban landscape ET is estimated using ET<sub>0</sub> and a landscape coefficient, which is a function of species, density, and microclimate factors. Based on the authors' knowledge in the study landscape as well as a report by CDWR [2000], we assume "Moderate" (trees and shrubs) and "High" (turf grass) water needs. Following the CDWR [2002]
instructions on irrigation zones with mixed water need categories (i.e., low, moderate, and high), a value from high category is selected (average species factor=0.80). Assuming the "average" category for vegetation density, a density factor of 1 is used. Furthermore, a "high" category of microclimate condition is used (microclimate factor=1.25) for the current highly developed study domain. This factor is utilized to take into account the contribution of the developed surfaces to the water loss from vegetated areas, through anthropogenic heating, reflected light, and high temperatures of surrounding heat-absorbing surfaces (e.g., paving and buildings). Using these factors, a landscape coefficient of 1 (landscape coefficient = species factor × density factor × microclimate factor) is prescribed. This coefficient and ET$_0$ estimations from ten CIMIS stations within close proximity of the study domain (Fig. 1a) are utilized to compute the urban landscape ET which is then used in validation processes of the Noah-UCM. ET output of the model is also evaluated against recent ET measurements in the greater Los Angeles area [Moering, 2011]. Moering [2011] employed a previously developed chamber approach to measure instantaneous ET in an irrigated and a non-irrigated park in the Los Angeles metropolitan area during WY (Water Year) 2011 (WY is defined as Oct. 1st of the previous year to Sep. 30th of the designated year). They reported an annual ET of about 1224 mm over the observed irrigated park, which is located within our study domain.

3.6. Sensitivity Study of Surface Parameters

3.6.1. Temporal Evaluation

The monthly time series of the default Noah-UCM and remote sensing based GVF, ISA, albedo, and LAI are compared and modeled cumulative monthly sensible and latent heat fluxes, using default and newly estimated parameters, are presented over fully vegetated, low intensity
residential, and industrial/commercial areas (Fig. 2). Fluxes from high intensity residential areas are not presented as they behave similarly to those from the industrial/commercial areas. Except for the summer months, GVF values are significantly increased throughout the year when remote sensing products are utilized (Fig. 2a). Moreover, the default seasonal variations of GVF values, assumed over all the land cover types, are not detected in Landsat imagery (Fig. 2a). The reason for this is the significant and year round irrigation in the Los Angeles area, which is not accounted for in the default parameter tables. GVF plays a dominant role in the Noah-UCM simulations as it defines the vegetated fraction of the natural areas, and specifies albedo, LAI, emissivity, and roughness length values from the predefined ranges in the model lookup tables. Furthermore, GVF partitions the total ET between soil direct and canopy ET. The simulated latent heat flux is considerably decreased (up to 38,642 W m\(^{-2}\) per month) in the summer time and increased over the remaining months, when remotely sensed GVF is incorporated in the fully vegetated areas (Fig. 2b). Since any increase of latent heat flux that does not alter the radiative balance leads to a reduction in sensible flux, the newly developed GVF values, in turn, cause enhancements (up to 28,607 W m\(^{-2}\) per month) in the simulated summer sensible heat fluxes and a reduction in the sensible heat fluxes during the remaining months (Fig. 2b). Latent and sensible heat fluxes from the low intensity residential pixels show similar but less significant changes (up to 18,354 and 8,616.5 W m\(^{-2}\) per month, respectively), when the new parameter sets are implemented. Adding remotely sensed GVF causes insignificant changes in the industrial/commercial area fluxes due to the small percentage of vegetated land cover in such areas (Fig. 2d).
Figure 8. Monthly time series of default Noah/UCM compared with remote sensing based GVF, ISA, albedo, and LAI (a, e, i, and m) and modeled cumulative monthly sensible and latent heat fluxes (W m$^{-2}$) over fully vegetated, low intensity residential and industrial/commercial areas using the default and newly estimated parameters: (b-d) GVF, (f-h) ISA, (j-l) albedo, and (n-p) LAI.

There are also large deviations between the look-up-table-based ISAs and the remotely sensed values. Averaged ISA is decreased (10%) over industrial and commercial pixels and increased (49%) over low intensity residential areas, when remote sensing products are utilized in the parameter estimation process (Fig. 2.e). These changes in the impervious surface area, or urban fraction values, have significant effects on monthly latent and sensible heat fluxes over the developed pixels (Fig. 2g and 2h), due to the critical role of urban fraction in partitioning of the energy fluxes. Over the low intensity residential areas, higher ISA values minimize the effects of urban vegetation which leads to latent heat fluxes decreases (up to 17397 W m$^{-2}$ per month) and
sensible heat fluxes increases (up to 14558 W m\(^{-2}\) per month), throughout the year, when remotely sensed data replace default urban fractions (Fig. 2g). These changes are reversed and less significant over the industrial and commercial pixels (maximum latent and sensible heat flux changes of 8340.2 and 7350.8 W m\(^{-2}\) per month, respectively; Fig. 2h). ISA has no influence on the fluxes from fully vegetated pixels which do not include impervious areas (Fig. 2.f).

Considerable changes in the monthly albedo averages are detected when incorporating remote sensing data in the parameterization process (Fig. 2i). Using fused Landsat and MOSID products, a reduction of averaged albedo values is observed over the fully vegetated and residential areas (up to 48\% and 39\%, respectively; Fig. 2i). Moreover, the default seasonal variations are hardly noticeable in the remote sensing based albedo values, which is due to the consistent greenness in the study area from irrigation throughout the year. On the other hand, considerable albedo increases (up to 39\%) are detectable over the industrial/commercial pixels (Fig. 2i), which are caused by bright and highly reflective materials seen mainly over the rooftops of industrial/commercial buildings. Albedo affects the radiative energy budget and consequently available energy for the turbulent fluxes. In the current study, decreased albedo values over the fully vegetated and low intensity residential areas result in reduced loss of solar and long wave radiation respectively and, in turn, increases the sensible heat flux (up to 9401.6 and 5972.2 W m\(^{-2}\) per month; Fig. 2j and 2k). Albedo induced sensible heat decreases over industrial/commercial pixels are also noticeable (up to 9405.4 W m\(^{-2}\) per month; Fig. 2l).

Distinct seasonal fluctuations of LAI are observed in the remotely sensed data and the default parameter tables (Fig. 2m). This reflects the fact that landscape plantings are quite different from agricultural crops due to their being composed of collections of vegetation species and affected by complex irrigation patterns which are not taken into account in the vegetation parameter
tables in the Noah LSM [CDWR, 2000; Vahmani and Hogue, 2013; 2014]. Over the heavily vegetated pixels, the default pattern is reversed in the measured parameter sets with less seasonal variations and peaks in the winter time, due to the fact that most of the precipitation occurs in the winter months, over the current study domain (Fig. 2m). The industrial and commercial pixels illustrate higher LAI values in the remotely sensed parameter maps, year round, when compared to the default values (Fig. 2m). LAI is a critical parameter in the Noah LSM, which is involved in the parameterization of the canopy resistance, controlling canopy ET rates. In the presented results (Figs. 2n and 2o), LAI induced changes in the simulated turbulent fluxes are more apparent in the summer months and over fully vegetated and residential pixels, where sensible heat fluxes are significantly increased (up to 15,898 and 24,026 W m$^{-2}$ per month, respectively) and latent heat fluxes are significantly decreased (up to 18,187 and 27,199 W m$^{-2}$ per month, respectively). This is due to the considerable deceases in the LAI values in summer time which lead to elevations of the canopy resistance and therefore reductions of the transpiration from the vegetation, causing decreases in latent heat fluxes. This in turn partitions the net radiation more into sensible heat fluxes. LAI does not affect fluxes from industrial/commercial pixels with small pervious fractions (Fig. 2p). It is worth mentioning that changes in the turbulent fluxes time series, in particular the latent heat flux decreases in the summer months induced by implementation of satellite based LAI, are to some extent captured in the simulations with the remote sensing based GVF (compare Fig. 2b with 2n and 2c with 2o). This reflects our previous point that GVF controls assigned LAI values to vegetated pixels in the Noah LSM and that realistic presentation of GVF in the modeling framework can enhance LAI inputs in the model when LAI measurements are not available.
Remotely sensed emissivity maps are also utilized to replace the default values in the Noah-UCM simulations, which results in changes in the emissivity values (up to %5.1). However, the new surface parameterization leads to insignificant changes in turbulent fluxes (results now shown). The largest emissivity induced alterations in sensible heat fluxes are seen over industrial and commercial pixels (up to 8671.8 W m$^{-2}$ per month). Latent heat fluxes are changed, the most significantly, over fully vegetated areas (up to 710.82 W m$^{-2}$ per month).

3.6.2. Spatial Evaluation

The spatial distributions of newly assigned GVF, ISA, albedo, and LAI are next compared with those based on the Noah-UCM lookup tables. Different urban surface parameterizations, along with their impacts on the simulated maps of turbulent sensible and latent heat fluxes, are presented (Fig. 3; Valid at 1100 LST on 14 April 2011). As expected, during the spring period (April), GVF values are significantly higher when remote sensing products are utilized, due to the irrigation effects which are ignored in the default parameters (Fig. 3a and 3b). Over fully vegetated and low intensity residential pixels, where a significant portion of the energy goes into evaporation and transpiration, latent heat flux increases (about 300 and 230 W m$^{-2}$, respectively) and sensible heat fluxes decreases (about 160 and 120 W m$^{-2}$, respectively) are found (Fig. 3c and 3d) when utilizing the remote sensing GVF.

The spatial distributions of ISA, or urban fraction, between the remote sensing and default values show similar patterns (Fig. 3e and 3f). However, industrial/commercial and high intensity residential areas are assigned noticeably higher urban fraction values in the remote sensing based maps (compare Fig. 3e and 3f) which leads to lower latent heat fluxes (bias of up to about 130 W m$^{-2}$) and higher sensible (bias of up to about 100 W m$^{-2}$) in these pixels (Fig. 3g and 3h).
Figure 9. Spatial distributions of remote sensing based GVF, ISA, albedo, and LAI (a, c, i, and m) compared with those based on Noah/UCM lookup tables (b, f, j, and n) and simulated maps of turbulent sensible and latent heat fluxes using default and remotely sensed urban surface parameters: (c and d) GVF, (g and h) ISA, (k and l) albedo, and (o and p) LAI. Valid at 1100 LST on 14 April 2011.

The Noah-UCM parameters underestimate surface albedo values over highly urbanized pixels (Fig. 3i and 3j). In particular, the industrial/commercial buildings with highly reflective rooftops are ignored in the default parameterization. Over the highly vegetated areas, however, albedo
values are overestimated in look-up tables. Altering the energy budget, the newly developed albedo datasets lead to lower Noah-UCM-simulated sensible heat fluxes over intensely developed pixels and higher fluxes over the vegetated areas (Fig. 3k). The sensible heat flux differences are the most significant over industrial/commercial pixels (up to ~300 W m\(^{-2}\); Fig. 3k). The changes in absolute surface albedos do not affect simulated latent heat fluxes (Fig. 3l).

The remote sensing data detect higher LAI values over all pixel types, particularly over fully vegetated areas where new LAI values are significantly higher (Fig. 3m and 3n). By influencing the canopy resistance, these changes redefine the spatial distribution of turbulent fluxes (Fig. 3o and 3p). Over the densely vegetated areas, increases in latent heat flux (up to 50 W m\(^{-2}\)) and decreases in sensible heat flux (up to 35 W m\(^{-2}\)) are found (Fig. 3o and 3p). It is noteworthy that, as illustrated before (Fig. 3n and 3o), the most significant influences of LAI alterations are detected in the summer months. Thus, it is not surprising that the turbulent fluxes do not show significant sensitivity to the LAI changes in April.

Remotely sensed emissivity maps, implemented in the Noah-UCM simulations, show minimal effect on the output turbulent fluxes maps (results not shown). Our results (Fig. 2 and 3) agree with previous sensitivity studies performed with the Noah-UCM which indicated high sensitivity of the model to GVF, ISA, albedo, and LAI, and less model sensitivity to emissivity [Loridan et al., 2010; Wang et al., 2011]. Loridan et al. [2010] highlighted the critical role of ISA and LAI in the simulations of latent heat flux and albedo role in the sensible heat flux simulations. Investigating the peaks of diurnal turbulent fluxes, Wang et al. [2011] reported that latent heat flux is the most sensitive to the GVF. They also found that emissivity has minimal effects on the model outputs.
3.7. Evaluation of Noah-UCM Performance

After initial sensitivity tests, the model performance in reproducing ET and LST fields is evaluated using remotely sensed (independent from derived parameters) and in situ measurements. The comparisons of observed and simulated ET and LST, using different urban surface parameterizations (scenarios 1, 7, 8, and 9 in Table 1), are presented in figures 4, 5, and 6.

3.7.1. ET Simulations

The temporal variations of ET, simulated by the Noah-UCM model over fully vegetated pixels, are evaluated against CIMIS based ET measurements, spanning 2010 and 2011 (Fig. 4). The model reproduces similar ET behaviors when the default parameters and the second group of remotely sensed parameters (albedo, LAI, and Emissivity) are implemented (Fig. 4a and 4c). The ET differences between observations and the default simulation are minimal in the winter and fall months, due to the limited energy available for ET in those months. Over the warmer months, the observed and modeled ETs show distinct behaviors. CIMIS stations report two peaks, one in the spring and one in the summer time. Simulated ETs, however, illustrate one peak in the July. The Noah-UCM, using these parameterizations, underestimates ET rates for the most of winter and spring months and overestimates them in the summer time (Fig. 4a and 4c). Including remotely sensed albedo, LAI, and emissivity does not change the general seasonal pattern deviations of ET (Fig. 4a and 4c), but it reduces the biases considerably (with $R^2=0.83$ and RMSE=14.32 mm/month). We note that model improvement is mostly associated with inclusion of remotely-sensed LAI maps in the model since albedo and emissivity have minimal influence on latent heat fluxes from heavily vegetated pixels (see Fig. 2j).
Figure 10. Noah/UCM simulated cumulative monthly ET over fully vegetated pixels using different urban surface parameterizations: scenarios (a) 1, (b) 7, (c) 8, and (d) 9 in the table 1 and their comparisons with CIMIS based ET measurements spanning 2010 and 2011. Scatter plots of these comparisons are also included (right).
The new GVF and ISA values alter ET seasonal fluctuations significantly in scenario 7 (Fig. 4b). In agreement with CIMIS observations, the model with inclusion of remotely sensed parameters results in significantly higher ET values in the warming months (Feb.-May) and lower ETs in the summer time. Noting that ISA has minimal effects over the fully vegetated pixels, one explanation for this pattern is that higher green vegetation fraction detected by Landsat in late winter and early spring, increases transpiration rates as soon as the required energy is available and lower measured GVFs in the summer time suppresses the transpiration rates, resulting in the lower ET values. These changes enhance the model performance significantly (with $R^2=0.92$ and RMSE= 11.77 mm/month).

Including all the measured parameter sets (Fig. 4d), reduces the behavioral disagreements between observed and modeled monthly ET ($R^2=0.86$). Large biases over the summer months are also reduced. However, ET values are overestimated over the rest of the year (RMSE=17.49 mm/month). Although each newly developed parameter group enhances the model performance in predicting ET, the advantages are countered when all of the parameters are implemented in the model. This is possibly due to the complex interactions between the parameters (e.g. GVF and LAI) in the model structure.

A notable pattern detected by CIMIS data is the drop in ET values over the month of June. The sudden decrease in ET corresponds to the June Gloom weather pattern in southern California, when onshore flows result in persistent overcast skies with cool temperatures, as well as fog and drizzle in late spring and early summer [NWS, 2011]. The June Gloom effects are captured in scenarios 7 and 9 (Fig. 4b and 4d) and not seen in scenarios 1 and 8 (Fig. 4a and 4c). Since ISA has minimal influence on ET from the fully vegetated pixels and the second group fails to
simulate June Gloom influence, the improvements in scenarios 7 and 9, in capturing this phenomenon, are associated with a more accurate representation of GVF.

3.7.2. LST Simulations

In order to further evaluate model performance and examine the impacts of different remote sensing based parameter sets, Landsat based LST measurements are utilized (Fig. 5 and 6). Statistics (R\(^2\) and RMSE) are also included to quantify the model performance using different urban surface parameterizations (Fig. 5). The observed LSTs, over fully vegetated pixels, are estimated with fair accuracy by the default model (R\(^2\)=0.86 and RMSE=3.21 °C; Fig 5a). The model performance is slightly worse (~1°C) over low intensity residential areas (Fig. 4e). Using remote sensing data weakly improves the biases (with <1°C improvement; Fig. 4b-d and 4f-h).

Over industrial/commercial areas, a systematic underestimation of the observed LST is identified (R\(^2\)=0.62 and RMSE=6.15; Fig. 4i). Both remotely sensed parameter groups (scenarios 7 and 8) significantly improve the correlations between the observed and simulated LSTs (RMSE of 0.76 and 0.70, respectively; Fig. 4j and 4k). When all the parameters are used (scenario 9), the RMSE is enhanced to 0.82. However, the cold biases are persistent in all simulations (Fig. 4j-l).

A comparison of LST at 1100 LST on 14 April 2011 with four simulation cases is also presented (Fig. 6). Alterations due to use of remote sensing products are more noticeable in this spatial examination of the results. Using all the default parameters (scenario 1), observed LST is overestimated over the heavily vegetated areas and underestimated over highly developed pixels (Fig. 6a and 6b). Remotely sensed GVF and ISA (in scenario 7) significantly decrease LSTs over fully vegetated and low intensity residential pixels and increase temperatures over industrial and
commercial areas result in a better match with the observed LST map. However, the model still underestimates the observed LSTs over the industrial and commercial pixels (Fig. 6b and 6e).

Figure 11. Scatter plots of observed (Landsat-based) versus simulated LSTs averaged over different land cover types using different urban surface parameterizations, including scenarios 1 (first row), 7 (second row), 8 (third row), and 9 (forth row) in Table 1.
The decreased simulated surface temperatures over heavily vegetated areas is due to higher GVF and consequently higher ET rates, which in turn lead to lower sensible heat flux and LSTs (see Fig. 3b). The increased LSTs over highly developed areas is likely due to lower GVF and higher ISA values detected in Landsat imagery, compared with the default values, which partition net radiation more into sensible heat flux (see Fig. 3b and 3f). The noticed changes in LST maps, using remotely senses albedo, LAI, and emissivity (scenario 8), are small (compare Fig. 6a and 6e). Although simulated LSTs over fully vegetated areas are decreased, the observed temperatures are still overestimated (Fig. 6f). The LST decreases in scenario 8 may be explained by evaporative cooling effect of the higher LAI values over heavily vegetated areas (see Fig. 3n). Similar to scenario 7, considerable GVF induced LST reductions, over fully vegetated areas, improve the observed LST estimations in scenario 9 (Fig. 6h). Our assessment indicates that implemented satellite derived parameter maps, particularly GVF and ISA used in scenarios 7 and 9, enhance the Noah-UCM capability to reproduce the LST differences between fully vegetated pixels and highly developed areas (simulated LST differences of 1.31, 4.81, 1.55, and 4.93 °C for scenarios 1, 7, 8, and 9 vs. observed LST difference of 11.25 °C). Nevertheless, the model still underestimates remotely sensed LST values, by about 9.91 °C for scenario 9, over the highly developed areas.

Further analysis (not shown here) indicates that the underestimation of LST values, particularly over high intensity residential and industrial/commercial areas, is due to a fundamental problem in the UCM and cannot be immediately solved with available parameter choices. This problem is discussed in a related study investigating different schemes for LST and conductive heat fluxes in the UCM [Wang et al. 2011b]. Their study shows that the current UCM formulation results in a phase lag and cold biases in simulated surface temperature when compared to observations.
The discussed cold biased could potentially be resolved utilizing a spatially-analytical scheme introduced by Wang et al. [2011b].

![Figure 12. Noah/UCM simulated LST maps using different urban surface parameterizations: scenarios 1, 7, 8, and 9 from Table 1 (top row) as well as differences between simulated and observed land surface temperature at 1100 LST on 14 April 2011 (bottom row).]

### 3.7.3. Energy and Water Budget Evaluation

Differences in the simulated energy and water budgets, with different surface parameterizations (scenarios 1, 7, 8, and 9 in the Table 1) are summarized for WY 2011 (Fig. 7). The emissivity induced changes to the energy and water budgets are insignificant and not included. The illustrated radiative and turbulent heat fluxes show that, unlike the longwave radiative fluxes, the simulated available solar radiances are altered considerably using different urban parameter sets (up to %6), particularly over fully vegetated (Fig. 7a) and industrial/commercial pixels (Fig. 7c). These changes are induced by new surface albedo values utilized in scenarios 8 and 9. It is also observed that most of the incoming radiative energy is dissipated through latent heat fluxes, over
heavily vegetated pixels (Fig. 7a and 7b), and sensible heat fluxes over industrial/commercial areas (Fig. 7c). These turbulent fluxes are also altered when different surface parameterizations are incorporated. Implementing all the remotely sensed parameters (scenario 9), the annual latent heat flux is increased (12%) over fully vegetated pixels (Fig. 7a), and the annual sensible heat flux is decreased (32%) over industrial/commercial pixels (Fig. 7c). Ground heat fluxes, however, are insignificant and unchanged.

Figure 7. Differences in simulated energy (top) and water (bottom) budgets for WY 2011, using different urban surface parameterization and averaged over different land cover types.

Water budget terms also show variable behavior using different parameter sets over different land cover types (Fig. 7 d-f). Annual irrigation amounts exceed received precipitations over the pixels with significant vegetation fractions (Fig. 7d and 7e). This pattern is not rare in semi-arid regions [CDWR 1975, Mini et al., 2014]. In these areas, most of incoming water is lost through
ET (Fig. 7d and 7e). Areas with high coverage of impervious surfaces, however, dissipate most of the incoming moisture through surface runoff (Fig. 7f). The alterations in the annual ET rates are, for the most part, due to the changes in the GVF parameterizations (scenarios 7 and 9; Fig. 7d-f). Sub-surface runoff annual rates, on the other hand, are altered using new ISA values (scenarios 7 and 9; Fig. 7e and 7f). Changes in the annual ET values are as large as 145, 156, and 79.4 mm over fully vegetated, low intensity residential and industrial/commercial pixels, respectively (Fig. 7d-f).

To further verify the capability of Noah-UCM to reproduce observed ET quantities, additional evaluation of the model is conducted utilizing ground-based chamber ET measurements in the greater Los Angeles area [Moering, 2011]. Instantaneous ET measurements, over an irrigated park in the study domain during WY 2011, are converted to daily and then annual ET estimates (1224 mm) and compared with the simulated ET values over the parks (Fig. 7d). As expected, the observed ET is best reproduced by scenario 7 (Bias of 1.47 mm) due to more accurate representation of GVF in the model. Scenarios 1 (with the default parameters) and 8 underestimate, with biases of 58.65 and 65.32 mm, respectively. Scenario 9, with all the remotely sensed parameters, overestimates the measured ET (with bias of 86.24 mm). These shortcomings are likely due to: (1) a lack of accurate representation of GVF in the default parameter sets, used in scenarios 1 and 8, (2) the uncertainties associated with the estimated LAI values utilized in scenarios 8 and 9, and (3) complex interactions between GVF and LAI noted in scenario 9.

The presented analysis of energy balance (Fig. 7) suggests that GVF, albedo and LAI play an important role in regulating simulated radiative energy budget and turbulent fluxes, mainly by
affecting the available net radiation and transpiration quantities. GVF, ISA, and LAI also alter the study area transpiration and ET values, as well as surface runoff rates.

3.8. Conclusions

In the current work we investigate the utility of a select set of remote sensing based surface parameters in the Noah-UCM modeling framework over a highly developed urban area. It was found that remote sensing data show significantly different magnitudes and seasonal patterns of GVF when compared with the default values. The reason for this mismatch is the significant and year round irrigation in the Los Angeles area which is not accounted for in the default parameter tables. The noticed differences between the monthly LAI values from default tables and remotely sensed data are also due to complex irrigation patterns. Another factor that contributes to this mismatch is the fact that landscape plantings are quite different from agricultural crops due to their being composed of collections of vegetation species which is not taken into account in the vegetation parameter tables in the Noah LSM [CDWR, 2000; Vahmani and Hogue, 2013; 2014]. There are also considerable deviations between the look-up-table-based ISA, albedo and emissivity maps and the remotely sensed values. The results of our analysis agree with previous studies which show high sensitivity of the Noah-UCM to GVF, ISA, albedo, and LAI, and minimal model sensitivity to emissivity [Loridan et al., 2010; Wang et al., 2011]. Our results show that GVF, ISA and LAI are critical in the simulations of latent and sensible heat flux, and that albedo plays a key role in the sensible heat flux simulations.

Our assessment of the Noah-UCM ET estimation shows that using the default parameters leads to significant errors in the model predictions of monthly ET fields (RMSE= 22.06 mm/month) over the study domain in Los Angeles. Results show that accurate representation of GVF is
critical to reproduce observed ET patterns over vegetated areas in the urban domains. LAI also plays an important role in ET simulations. However, simulations incorporating the remotely sensed GVF values outperform (RMSE= 11.77 mm/month) simulations with the new LAI estimates (RMSE=14.32 mm/month). This could be due to several reasons. First, there are uncertainties associated with the remote sensing based LAI retrieval, including non-linearity of LAI-vegetation index (RSR) relationships [Latifi and Galos, 2010], which do not apply to NDVI-based GVF. Second, more accurate representation of GVF values in the Noah-UCM not only improves the assigned LAI values to the vegetated pixels in the model but also enhances other parameters inputs as well (i.e. albedo, emissivity, and roughness length). Further analysis of the model performance indicates that implemented satellite derived parameter maps, particularly GVF and ISA, enhance the Noah-UCM capability to reproduce the LST differences between fully vegetated pixels and highly developed areas (simulated LST differences of 1.31 and 4.81 °C for scenarios with default and remotely sensed GVF and ISA vs. observed LST difference of 11.25 °C). Nevertheless, the model still underestimates remotely sensed LST values, over highly developed areas. We speculate that the underestimation of LST values, particularly over high intensity residential and industrial/commercial areas, is due to structural parameterization in the UCM and cannot be immediately solved with available parameter choices.

Our analysis of energy balance suggests that GVF, albedo and LAI play an important role in regulating simulated radiative energy budget and turbulent fluxes, mainly by affecting the available net radiation and ET quantities. With regard to urban water balance, GVF, ISA, and LAI play a key role in surface hydrologic fluxes, including ET and surface runoff. When compared with in-situ observations, Noah-UCM shows the capacity to reproduce ET fields with
relatively high accuracy (Bias of 1.47 mm) when GVF maps are updated using remote sensing data.

In summary, the current study highlights the significant deviations between the spatial distributions and seasonal fluctuations of the default and remotely sensed parameter sets in the Noah-UCM. We illustrate that replacing default parameters with the measured values reduces significant biases in model predictions of the surface fluxes within irrigated urban areas. This ultimately has key implications in feedback processes to the atmosphere when the Noah-UCM is coupled with the widely used WRF model, which has been increasingly applied over urban areas to examine the exchange of heat, moisture, momentum or pollutants. Semi-arid urban cities are receiving much attention in the literature, given their accelerated growth and increasing dependence on external water sources. More accurate representation of both water and energy fluxes is critical for regional resource management as well as predictions of urban processes under future climate conditions.

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3.9. References


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Chapter 4. Urban irrigation effects on WRF-UCM summertime forecast skill over the Los Angeles metropolitan area

4.1. Introduction

Urbanization is a demographic trend worldwide. More than half of the world's population inhabited cities in 2008 and it is expected that more than 80% of the global population will reside in urban areas by 2030 [UNFPA, 2007]. It is found that half of all cities with populations greater than 100,000 are located in water scared watersheds [Richter et al., 2013]. These cities, particularly the ones located in arid and semi-arid regions (e.g., Phoenix, Arizona, Los Angeles and San Diego, California), are heavily dependent on the imported water as the local supplies are exhausted [Richter, 2013]. Urban irrigation is an important component of water cycles in these regions where planted vegetation may not be adapted to the local climate and requires additional watering. For instance 14-30% of municipal water consumption in California is used for irrigation [Gleick et al., 2003]. Hence, understanding the effects of urban irrigation on the local and regional water budgets is imperative to enhance sustainable water resources management and help develop effective adaptive strategies in arid and semi-arid regions.

Studies that take urban irrigation in their considerations are limited to several water balance studies that apply the principle of mass conservation in the hydrological cycle of the developed regions [Mitchell et al., 2001; 2008; Jarvi et al., 2011]. Mitchell et al. [2001] includes water supply, wastewater, and storm water components within their water balance modeling framework (Aquacycle). The model is designed to keep soil moisture at a specific minimum level necessary to maintain the plant health and growth rate, mimicking effects of irrigation. Over Canberra, Australia, Mitchell et al. [2008] reported that imported water, storm water, and
evapotranspiration (ET) components in the simulated water budget are highly sensitive to the changes in irrigation water. Jarvi et al. [2011] developed an urban energy and water balance scheme which calculates irrigation water using a simple hourly model and diurnal water profiles, based on a local survey and bi-monthly water bills gathered by Grimmond et al. [1996] over the city of Los Angeles. These studies confirmed that irrigation is an important component of urban water cycle, particularly in arid and semi-arid regions [Mitchell et al. 2001; Jarvi et al. 2011].

The Weather Research and Forecasting (WRF) model [Skamarock et al. 2008], a regional atmospheric model, has been widely used for simulation of urban-atmosphere heat, moisture, and momentum exchanges since the single layer Urban Canopy Model (UCM) [Kusaka et al., 2001; Kusaka and Kimura, 2004] was installed. The main focus of the UCM developers has been to improve the simulation of thermodynamics, dynamic and thermal storage effects in urban canyons, by incorporating the buildings' role in trapping and reflection of shortwave and longwave radiation. Many studies have shown benefits of using WRF-UCM modeling framework to better understand the impacts of urbanization on the local and regional climate [Zhang et al., 2010; Feng et al., 2012] and the meteorological fields in the lower atmosphere [Miao et al., 2009; Loridan et al., 2010; Flagg and Taylor, 2011], urban heat islands [Georgescu et al., 2011; Loughner et al., 2012; Wang et al., 2013], and urban induced changes of precipitation [Shem and Shepherd 2008; Lin et al., 2011]. Few urban simulation studies have focused on the effects of canyon vegetation on surface temperature and turbulent fluxes [Loughner et al., 2012; Lee and Park, 2008]. Although some studies recognized the lack of urban irrigation representation as a deficiency that the urban canopy modeling faces [Loridan et al., 2010; Georgescu et al., 2011], very few modeling studies account for anthropogenic sources of moisture in their study domains. Loridan et al. [2010] highlighted that this limitation alters the
partitioning of turbulent energy between latent and sensible fluxes and chose a vegetation type with a low stomatal resistance (e.g. 'cropland mosaic' or 'grassland') to mimic the irrigation effects. Georgescu et al. [2011] accounted for irrigation by setting the second (10-40 cm depth) and third (40-100 cm depth) soil layers, for the low-intensity residential areas, to a reference soil moisture content below which transpiration begins to stress. They concluded that urban irrigation effects on the near surface temperatures and surface energy budget components are limited. Coleman et al. [2010], utilized monthly CIMIS based ET, normalized by annual total ET values, to define simulated source of anthropogenic moisture in their WRF-UCM modeling frame work over southern California. Significant irrigation induced cooling and modest improvement in WRF forecast skills were reported. They also pointed out that more research is necessary to better understand the physical processes that distribute the anthropogenic moisture during WRF forecast period. The irrigation impacts reported by these studies do not agree due to the different approaches employed by the authors to account for anthropogenic soil moisture contribution. We believe there are still many unknown aspects regarding the accurate representation of urban irrigation in the numerical modeling frame works.

In this study we will explicitly addressed the impacts of urban irrigation by integrating a previously developed irrigation scheme within the coupled framework of the WRF-UCM over the semi-arid Los Angeles metropolitan area. A key question relates to physical mechanisms and components that define urban water budget in water scarce regions. With evaluating the role of irrigation in the urban water cycle and a focus on urban ET, this work is likely to shed further light on water cycles and atmospheric feedback in arid and semi-arid cities. Our objective is to build upon previous work, focusing on improving the representation of irrigated urban vegetated in the numerical weather prediction models which are now standard tools to study urban-
atmosphere interactions. The enhanced modeling framework will potentially improve our understanding of urbanization impacts on the boundary layer processes, near surface meteorological fields, and local and regional climate. We focus on the month of July as previous studies reported the most significant irrigation induced changes in ET fluctuations occur during this month [Vahmani and Hogue, 2014a].

4.2. Methods

4.2.1. WRF-UCM Modeling Framework

We use version 3.5.1 of the WRF [Skamarock et al. 2008] modeling framework to conduct high spatial resolution (1 km grid spacing within the innermost domain) sensitivity experiments to urban irrigation over the Los Angeles metropolitan area. A detailed description of utilized options, domain extent, forcing data, and irrigation incorporation are presented below.

WRF is a fully compressible, non-hydrostatic model with mass coordinate system that has been used extensively applied in urban areas. We use the North American Regional Reanalysis (NARR) data set [Mesinger et al., 2006] to initialize and force WRF, at the lateral boundaries. Simulations for all experiments were conducted over the month of July, 2011. We used three nested grids, centered over the Los Angeles metropolitan area with a grid spacing of 20, 4, and 1 km (Figure 1). The vertical grid contains 38 layers levels from the surface to 50 hPa. The physical parameterization used here include the Monin-Obukhov scheme for the model surface layer, the Yonsei University (YSU) scheme [Hong et al. 2006] for the model planetary boundary layer (PBL), the Kain-Fritsch scheme [Kain 2004] for the cumulus parameterization, the WRF single-moment three-class scheme for microphysics [Hong et al., 2004], the Rapid Radiative

The four-layer Noah land surface model (LSM) [Chen and Dudhia, 2001] is use to simulate natural surfaces in the study domain. To parameterize urban land surface processes, we make use of the single-layer Noah Urban Canopy Model (UCM) [Kusaka et al., 2001; Kusaka and Kimura, 2004], which has a medium complexity among urban parameterizations incorporated within WRF. This model assumes infinitely long street canyons and takes into account the three dimensional nature of urban surfaces, shadowing, reflections, and trapping of radiation in the urban canyon as well as an exponential wind profile [Chen et al, 2011].

The first challenge in numerical weather perdition modeling of urban regions is accurate representation of the extent and intensity of urban areas [Holt and Pullen, 2007; Chen et al., 2011]. The urban area categories for the Los Angeles metropolitan area are defined by using the USGS 2006 National Land Cover Data set (NLCD) based on the 30 m Landsat satellite data (Fig. 1). The NLCD data set divides the developed land use into four classes: industrial/commercial, high intensity residential, low intensity residential, and open space which is a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. This level of detailed urban classification is necessary for characterizing urban geometry, thermal and hydrologic characteristics, natural/developed land coverage which are required by sophisticated urban models such as UCM. It should be noted the radiative, latent, and sensible heat fluxes calculated by Noah LSM and UCM are coupled using a tile approach and urban fraction parameter. In the current study urban fractions of 0.9, 0.65, and 0.25 are used for industrial/commercial, high intensity residential, and low intensity residential pixels (which includes both low intensity residential and open space areas in the NLCD data set), respectively.
These numbers are adopted from a previous study [Vahmani and Hogue, 2014b] in Los Angeles area which utilized fused MODIS and Landsat data to define developed surface parameters including green vegetation fraction (GVF), impervious surface area (or urban fraction), albedo, leaf area index (LAI), and emissivity.

Urban irrigation is accounted for using a previously developed irrigation scheme based on a soil moisture deficit function which is the difference between irrigated soil moisture content and actual soil moisture content [Vahmani and Hogue, 2014a]. This module runs within the Noah LSM and simulated urban irrigation by updating the top soil layer moisture content, for irrigated pixels, to a certain percentage of soil saturation (irrigation demand factor) at a certain irrigation interval. The irrigation demand factor, via irrigated soil moisture content, defines an upper limit for the added soil moisture to the soil to prevent unrealistic heavy irrigation. In the current analysis, irrigation is assumed to be automatic and with no water loss (fully effective). Over the Los Angeles metropolitan area, Vahmani and Hogue [2014a] reported that irrigation demand factor of 65% and irrigation interval of three days represent the irrigation behavior with a reasonable accuracy based on their analysis of monthly water consumption records and the monthly outdoor water use estimates for 2010 and 2011. The same irrigation parameters are adopted for the developed pixels in the current study as every third day, the first (10 cm depth) soil layer of the Noah LSM corresponding to all urban classes are set to a reference volumetric soil moisture content (i.e., 65 percent of saturation soil moisture content).
4.2.2. Experiments Performed

As our main objective is to explore the effects of urban irrigation on the urban water budgets, we start with a 'control' or non-irrigation simulation with no anthropogenic water. We then run an irrigated simulation with irrigation added to the system. We use a one way nested grid configuration with three grids centered over the Los Angeles metropolitan (Fig. 1). All verification and analysis is presented over the urban areas encompassed by the innermost model domain (natural pixels are blocked), where the grid spacing is 1 km x 1 km. The simulations are conducted from 29 June, 0000 UTC to 31 July, 2300 UTC July 2011 allowing first 48 hours for model spin up. The NLCD land use land cover data and default urban and vegetation parameters, except for urban fraction, are used for all the simulations.
4.2.3. Observational Data

The source of ground based and remotely sensed measurements against which WRF performance is evaluated is described below.

We make use of hourly ground based observations from six CIMIS and thirteen National Climatic Data Center (NCDC) stations for the period from 1 to 31 July 2011. Of the total nineteen stations, only one station is located in an undeveloped area while the remaining are urban stations. The locations of the stations relative to one another and the extent of the innermost grid are shown in Figure 1b. The NCDC stations, which use Automated Surface Observing Systems (ASOS), are located at smaller local airports (12 stations), one major airport (Los Angeles International Airport) within the Los Angeles metropolitan area. NCDC stations report hourly meteorological conditions including wind speed, air temperature, relative humidity, air pressure, and incoming long wave radiation. All NCDC data are gathered at a standard reference height of 2m. The regional CIMIS stations provide real weather and climate conditions including hourly surface solar radiation, temperature, humidity, wind, precipitation, soil temperature, and surface pressure. Using observed meteorological fields over a well-watered soil, the reference ET (ET0) is also estimated at each site [http://wwwcimis.water.ca.gov/cimis]. In the current study reference ET, solar radiation (using LI200S pyranometer), precipitation (using tipping bucket rain gauges), temperature, and humidity data from six CIMIS stations within the study area (Fig. 1) are utilized in the evaluation processes of the WRF-UCM.

The land products of the MODIS data are used here to obtain land surface temperature (LST) spatial and temporal behavior over the study domain. MODIS is aboard both the Terra and Aqua satellites, which pass the equator two times per day [Wan 1999]. Over the Los Angeles, we use Terra MODIS data with local passing times of approximately 1100 and 2200 Local Time (LT).
MODIS has a high spatial resolution of 250 m in the visible and 1 km in the infrared channels. The MODIS 1-km LST data are derived through the generalized split-window algorithm and screening for clouds [Wan 1999; Wan et al. 2002]. The day/night characteristic of MODIS offers the possibility of studying the seasonal behavior of LST in the both morning and night hours. In this study the MOD11A2 product is used to obtain day and night time images of LST under clear-sky conditions during the month of July 2011.

4.3. Results

4.3.1. Sensitivity to irrigation

In the current section we assess the surface energy and water fluxes sensitivity to the incorporation of urban irrigation (Figs. 2, 3 and 4).

Figure 14. The spatial maps of latent, sensible, and ground heat fluxes from simulations with and without anthropogenic soil moisture contribution at 11:00 LT 20 July 2011.
Latent and sensible heat fluxes show strong sensitivity to the addition of irrigation to the vegetated pixels (Figure 2). The irrigation impacts on the ground heat flux spatial patterns are also noticeable. Surface energy fluxes sensitivity to irrigation closely follows the pattern of urban intensity with heavily vegetated (low intensity residential and developed open spaces) areas experiencing most significant irrigation induced changes. Introducing anthropogenic moisture, these areas show increased latent heat fluxes and decreased sensible and ground heat fluxes confirming irrigation induced shift in the energy partitioning between turbulent fluxes toward elevated latent heat fluxes.

Figure 15. Hourly fluctuations of latent and sensible heat fluxes before and after adding irrigation to the system for July 2011.
To evaluate the impacts of irrigation on the temporal variation of simulated turbulent fluxes, we present hourly latent and sensible heat fluxes before and after adding irrigation to the system for the month of July 2011 (Fig. 3). The simulated urban irrigation imparts increases (from 11 to 151 W m\(^{-2}\)) in peak (midday) latent heat flux (Fig. 3a) as well as decreases (from 33 to 139 W m\(^{-2}\)) in peak sensible heat flux (Fig. 3b). These impacts appear to intensify toward the end of the simulation time frame. We speculate that the initial conditions, particularly of the soil moisture, provided the required water by the vegetation in the no irrigation simulation. However, this limited source of water fades away every day resulting in more distinct differences between control and irrigated simulations.

The decreased air temperatures induced by simulated anthropogenic moisture contribution are more significant over the inland pixels, where the cooling effects of sea breeze weaken (Fig. 4).

![Near surface air temperature](image)

Figure 16. Spatial maps of near surface air temperature for urban pixels from control and irrigated simulations at 11:00 LT 20 July 2011.

Near surface temperature differences between irrigated and not irrigated pixels are generally between 0.5 and 1.5 °C (Fig. 4), highlighting the insignificant impact of irrigation on the air temperature patterns. This result is in agreement with previous studies [Georgescu et al., 2011] that did not notice a significant irrigation induced changes in air temperature fluctuations.
4.3.2. Impact of soil moisture initial conditions on water cycle

To determine the cause of the simulated increase in the irrigation induced changes of turbulent fluxes during the course of the July 2011 (Fig. 3), the moisture content of different soil layers from control and irrigated simulations are examined (Figs. 5, 6, and 7). The hourly fluctuations of moisture content in the first soil layer, before and after adding irrigation, are compared (Fig. 5). As expected, the top soil layer moisture is greater in the irrigation case throughout the simulation time frame. The regular jumps in the soil moisture level reflect the simulated irrigation effects which add water to the system at a three day interval (Fig. 5). The soil moisture in the control run is lower than the irrigated simulation and is descending through the month of July. This confirms that in the not irrigated simulation, the moisture stored in the soil layers by the defined initial conditions is used to provide required water to the vegetation.

![Figure 17. Hourly variations of WRF-UCM simulated soil moisture content at the top soil layer, before and after adding irrigation, for the July 2011.](image)

To further examine the simulated soil moisture variations, spatial moisture maps at different soil layers at the beginning (1 July) and the end (31 July) of the simulated time frame from both control (Fig. 6) and irrigated (Fig. 7) simulations are evaluated. It is evident, from an assessment
of Figure 6, that the soil moisture sorted in the four soil layers is consumed in the course of the month, for evaporation and transpiration, resulting in considerable decreases in the soil moisture levels in all layers (compare Figs. 6a, c, e, and g with 6b, c, g, and h, respectively).

Figure 18. Spatial maps of simulated soil moisture content at soil layers 1, 2, 3, and 4 (from the ground surface to the bottom) from control simulation at 11:00 LT for July 1st (top) and 31st (bottom).

Figure 19. As figure 6 but for irrigated simulation.
This pattern is not observed in the irrigated simulation as the required water for evapotranspiration processes is provided by simulated irrigation (compare Figs. 7a, c, e, and g with 6b, c, g, and h, respectively) causing soil moisture contents to be relatively constant during the month of simulation. Analysis of these results indicates the fact that the initial soil moisture level plays a principal role in disguising the real impacts of irrigation in urban domains and to see the actual impacts of urban irrigation the simulations should be conducted for a longer period of time than one month which is rare in WRF-UCM studies.

4.3.3. Evaluation of WRF-UCM

The hourly and daily variations of observed and simulated ET are presented in Figures 8a and 8b, respectively. It is possible, utilizing a methodology introduced by CDWR [2000] and a landscape coefficient, to convert the reference ET to actual urban landscape ET. Naturally, this method which is based on of species, density, and microclimate factors is associated with uncertainties. In the current study, to avoid these uncertainties, it is decided that hourly CIMIS evapotranspiration amounts provide an acceptable way to evaluate the model performance in reproducing the ET temporal fluctuations. WRF-UCM, after adding irrigation, performs reasonably during the course of the month, tracking day to day variability of ET with notable fidelity (Figs. 8a and b). The not irrigated case show similar ET fluctuations to the CIMIS based ET and irrigated case, in the first few days of simulations. Toward the end of the month, however, the differences between simulated ET and CIMIS based ET0 become more apparent (Fig. 8a and b) highlighting the impacts of depleting moisture levels in the soil layers as discussed in the last section.
A comparison of simulated and observed LST maps is presented for July 1st (Fig. 9a, c, and e) and 31st (Figs., 9b, d, and f) to examine the effects of depleting soil moisture in the control case as discussed in the last section. In general the observed LST values are underestimated by both control and irrigated simulations. This problem is discussed in a related study investigating different schemes for LST and conductive heat fluxes in the UCM [Wang et al. 2011b]. They confirm that the current UCM formulation results in a phase lag and cold biases in simulated surface temperature when compared to observations. In the current analysis we focus on the spatial LST patterns observed in the MODIS based maps including lower LST values over highly
vegetated pixels (circled in Figs. 9e and f). These decreased temperatures are evident in the simulated LST maps from both control and irrigated simulations in the beginning of the simulations (1 July: Figs. 9a and c). Increased latent heating due to high vegetation coverage in these areas is compensated by decreased sensible heating and LST. After 31 days of simulation, however, these patterns of lower LST values over more heavily vegetated pixels is lost in the control run (Fig. 9b).

Figure 21. Spatial variations of WRF-UCM simulated LST, before and after adding irrigation, evaluated against LST maps detected by MODIS at 11:00 LT for July 1st (top) and 31st (bottom).

This is due to fact that cooling effects of increased latent heat fluxes in vegetated areas is reduced as soil moisture is depleted. In the not irrigated simulation, the soil moisture is the only source of water in the absence of irrigation and significant precipitation. In the irrigated case, however, the cooling effects of urban vegetation are persistent throughout the simulation time.
frame (Fig. 9d), indicating the importance of accurate representation of urban irrigation in water scarce regions such as Los Angeles metropolitan area.

The simulated amplitudes and phases of the diurnal cycles of near surface temperatures are evaluated against hourly ground based measurements. The comparisons, utilizing the simulated air temperatures before and after adding irrigation and observed values from NCDC stations, are presented in Figure 10 for the month of July 2011. Both the control and irrigated simulations perform reasonably throughout the month, predicting similar magnitude to the observations. However, our results do not indicate a significant impact on air temperatures due to incorporation of irrigation within urban areas. We speculate that this, and similar conclusions made by previous studies [Coleman et al., 2010; Georgescu et al., 2011], could be due to the soil moisture initialization and short term WRF-UCM simulations which does not allow the actual irrigation induced changes to the surface energy and water budget components be disclosed.

![Figure 22](image.png)

Figure 22. Hourly variations of WRF-UCM simulated near surface air temperature, before and after adding irrigation, evaluated against NCDC based air temperature observations, for the July 2011.
4.4. Conclusions

In the current study, we have undertaken an initial sensitivity analysis and evaluation of the WRF regional climate model, coupled with UCM, over a semi-arid and water stressed metropolitan area with emphasis on the impacts of urban irrigation. We account for urban irrigation sources by integrating a previously developed irrigation scheme within the framework of WRF-UCM.

Our results demonstrate a significant sensitivity of surface turbulent fluxes to the incorporation of irrigation. Introducing anthropogenic moisture, the vegetated pixels show increased latent heat fluxes and decreased sensible and ground heat fluxes confirming irrigation induced shift in the energy partitioning toward elevated latent heat fluxes. These impacts appear to intensify toward the end of the simulation time frame. We speculate that the initial conditions, particularly of the soil moisture, provided the required water by the vegetation in the no irrigation simulation. However, this limited source of water fades away every day resulting in more distinct differences between not irrigated and irrigated simulations. This is confirmed when spatial and temporal variations of simulated soil moisture at different soil layers are evaluated throughout the simulated time frame from both control and irrigated simulations.

The evaluation of the model performance via comparison against CIMIS based reference ET indicates that WRF-UCM, after adding irrigation, performs reasonably during the course of the month, tracking day to day variability of ET with notable fidelity. In the absence of irrigation, simulated ET fluctuations are similar to the CIMIS based ET and irrigated case, in the first few days of simulations. Toward the end of the month, however, the differences between simulated ET and CIMIS based ET0 become more significant in the not irrigated case.
Analysis of the MODIS based LST spatial patterns highlight decreased temperatures in heavily vegetated pixels due to a shift toward greater latent heating and consequently lower sensible heating in these areas. This pattern is captured in the irrigated simulation throughout the simulation time frame. In the not irrigated case, however, these patterns are lost toward the end to the simulation month. This is due to the fact that, in the not irrigated simulation, the soil moisture is the only source of water in the absence of irrigation and significant precipitation. In the course of simulation, the soil moisture sorted in the soil layers is consumed, resulting in considerable decreases in the soil moisture levels in all layers. The soil moisture depletion leads to reduced latent heating and cooling effects of urban vegetation. Analysis of these results indicates the importance of accurate representation of urban irrigation in water scarce regions such as Los Angeles metropolitan area. Moreover, it is found that the initial soil moisture level plays a principal role in disguising the real impacts of irrigation in urban domains and to see the actual impacts of urban irrigation the simulations should be conducted for a longer period of time than one month which is rare in WRF-UCM studies.

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4.5. References


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Chapter 5. Conclusion and key contributions

The first part of the current study develops, incorporates and systematically evaluates an irrigation scheme within the Noah LSM-UCM framework. In the second part, we investigate the utility of a select set of remote sensing based surface parameters in the Noah-UCM over a highly developed urban area. The goal is not only to use the developed irrigation module and remotely sensed parameters to improve Noah LSM-UCM performance and thereby enhance WRF weather forecasts over arid and semi-arid urban areas, but also to establish a modeling tool for assessing the impacts of irrigation on urban meteorological fields. The developed modeling framework is applied over study areas in the Los Angeles metropolitan area at a high resolution to better understand the temporal variability and spatial heterogeneity of urban water fluxes in this region.

- What is the role of urban irrigation in the water cycle dynamics of semi-arid cities such as Los Angeles?

Across our study domain, irrigation water ranges from 607.4 to 60.13 mm/year. The highest/lowest applied water volume corresponds to the highest/lowest vegetation fraction and at a minimum over industrial and commercial regions. Meanwhile, the study area received a total of about 257 mm of rainfall during WY 2004. When compared to the non-irrigation simulation, the Noah LSM-UCM with irrigation produces much higher ET rates across the study domain. The irrigation-induced surface runoff variations are not remarkable due to the fact that significant surface runoff rates already occur over highly impervious lands, and minimal irrigation water is also applied for these areas. However, the irrigation-induced subsurface recharges are significant for more pervious surfaces. A 607.4 mm increase in annual hydrological inflow over fully vegetated areas corresponds to a 477.5 and 125.4 mm increase in ET and groundwater recharge,
respectively. In other words, over grassy areas, about 79% and 21% of extra water added to the surface is lost to evapotranspiration and subsurface runoff, respectively. These values scale to 83% and 9.3% for the entire study area. The LST predictions over the vegetation urban regions, before and after irrigation introduction, are also assessed. Our results show a 2 °C decrease in land surface temperature with the addition of irrigation in urban parks. 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 budget, hydrological fluxes and state variables.

- How well can an improved Noah LSM-UCM modeling framework perform over developed areas?

When compared to the instantaneous MODIS-Landsat ET product as well as the hourly CIMIS-based landscape ET observations, modeling results in the Los Angeles region indicate that the Noah LSM-UCM can simulate ET patterns at daily and monthly scales, when a reasonable irrigation module is incorporated. When evaluated against the LADWP residential records and the monthly outdoor water use data, the proposed irrigation scheme with an irrigation demand factor of 0.65 and irrigation interval of 3 days (one pulse every 3 days), reasonably represents irrigation fluxes over the study region. However, without irrigation, the model produces large biases in ET simulations, supporting our hypothesis that addition of an irrigation module is critical to adequately simulate the hydrologic cycle in the Los Angeles domain. The LST biases for parks and heavily vegetated areas, compared to the instantaneous Landsat LST product, are also reduced when the irrigation scheme is integrated in the model. Our analysis of the urban water budget confirms that the Noah LSM-UCM with the proposed irrigation scheme is capable of estimating the surface meteorological features with reasonable accuracy at the annual scale.
- How well do the default parameter sets within Noah LSM-UCM modeling framework define the unique characteristic of Los Angeles land surface? Does the use of monthly gridded remote-sensing based parameter sets enhance the model's predictive capabilities?

The results of our analysis agree with previous studies which show high sensitivity of the Noah-UCM to GVF, ISA, albedo, and LAI, and minimal model sensitivity to emissivity. Our results show that GVF, ISA and LAI are critical in the simulations of latent and sensible heat flux, and that albedo plays a key role in the sensible heat flux simulations. It was found that remote sensing data show significantly different magnitudes and seasonal patterns of GVF, ISA, albedo, LAI, and emissivity when compared with the default values in the Noah LSM-UCM modeling framework. The dominant reason for this mismatch is the significant and year round irrigation in the Los Angeles area which is not accounted for in the default parameter tables. Another factor that contributes to this deviation is the fact that landscape plantings are quite different from agricultural crops due to their being composed of collections of vegetation species which is not taken into account in the vegetation parameter tables in the Noah LSM.

Our assessment of the Noah-UCM ET estimation shows that using the default parameters leads to significant errors in the model predictions of monthly ET fields (RMSE= 22.06 mm/month) over the study domain in Los Angeles. Results show that accurate representation of GVF is critical to reproduce observed ET patterns over vegetated areas in the urban domains. LAI also plays an important role in ET simulations. However, simulations incorporating the remotely sensed GVF values outperform (RMSE= 11.77 mm/month) simulations with the new LAI estimates (RMSE=14.32 mm/month). This is due to the fact that accurate representation of GVF values in the Noah-UCM not only improves the assigned LAI values to the vegetated pixels in the model but also enhances other parameters inputs as well (i.e. albedo, emissivity, and
roughness length). Further analysis of the model performance indicates that implemented satellite derived parameter maps, particularly GVF and ISA, enhance the Noah-UCM capability to reproduce the LST differences between fully vegetated pixels and highly developed areas.

Our analysis of energy balance suggests that GVF, albedo and LAI play an important role in regulating simulated radiative energy budget and turbulent fluxes, mainly by affecting the available net radiation and ET quantities. With regard to urban water balance, GVF, ISA, and LAI play a key role in surface hydrologic fluxes, including ET and surface runoff. When compared with in-situ observations, Noah-UCM shows the capacity to reproduce ET fields with relatively high accuracy (Bias of 1.47 mm) when GVF maps are updated using remote sensing data.

“What impacts urban irrigation representation in numerical weather prediction models (e.g. WRF) has on the predicted urban water cycle and atmospheric feedback in arid and semi-arid cities?”

Our results demonstrate a significant sensitivity of WRF-UCM simulated surface turbulent fluxes to the incorporation of irrigation. Introducing anthropogenic moisture, the vegetated pixels show increased latent heat fluxes and decreased sensible and ground heat fluxes confirming irrigation induced shift in the energy partitioning toward elevated latent heat fluxes. The evaluation of the model performance via comparison against CIMIS based reference ET indicates that WRF-UCM, after adding irrigation, performs reasonably during the course of the month, tracking day to day variability of ET with notable fidelity. In the absence of irrigation, simulated ET fluctuations are similar to the CIMIS based ET and irrigated case, in the first few days of simulations. Toward the end of the month, however, the differences between simulated
ET and CIMIS based ET₀ become more significant in the not irrigated case. This is due to fact that, in the not irrigated simulation, the soil moisture is the only source of water in the absence of irrigation and significant precipitation. In the course of simulation, the soil moisture sorted in the soil layers is consumed, resulting in considerable decreases in the soil moisture levels in all layers. The soil moisture depletion leads to reduced latent heating and cooling effects of urban vegetation.

Analysis of these results indicates the importance of accurate representation of urban irrigation in water scarce regions such as Los Angeles metropolitan area. Moreover, it is found that the initial soil moisture level plays a principal role in disguising the real impacts of irrigation in urban domains and to see the actual impacts of urban irrigation the simulations should be conducted for a longer period of time than one month which is rare in WRF-UCM studies.