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Ariane Middel

Arizona State University at the Tempe Campus

Anthony J. Brazel

Arizona State University at the Tempe Campus

Patricia Gober

Arizona State University at the Tempe Campus

Soe Win Myint

Arizona State University at the Tempe Campus

Heejun Chang

Portland State University, changh@pdx.edu

See next page for additional authors

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Authors

Ariane Middel, Anthony J. Brazel, Patricia Gober, Soe Win Myint, Heejun Chang, and Jiunn-Der Duh

Land cover, climate, and the summer surface energy balance in Phoenix, AZ, and Portland, OR

Ariane Middel,^{a,*} Anthony J. Brazel,^b Patricia Gober,^{a,b} Soe W. Myint,^b Heejun Chang^c
and Jiunn-Der Duh^c

^a Decision Center for a Desert City, Arizona State University, Tempe, AZ, USA

^b School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA

^c Department of Geography, Portland State University, Portland, OR, USA

ABSTRACT: Changes in land use and land cover alter the local energy balance and contribute to distinct urban climates. This paper presents a local-scale above-canopy study of intra-urban land cover mixes in two cities to analyse the relative effects of surface morphology and local climate on the surface energy balance (SEB). The study is conducted for urban areas in Phoenix, Arizona, and Portland, Oregon, cities with distinct climates but similarly warm and dry summers. A Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) is used to analyse the relative contributions of local weather extremes and land cover variations on the urban energy balance. The partitioning of net all-wave radiation into turbulent sensible and latent heat fluxes as well as heat storage is investigated for a typical dry summer month and two extreme weather scenarios in the two cities. Results of sensitivity analyses show that incoming solar radiation is an important driver of the SEB in LUMPS and should be considered in the generation of climate scenarios. The relationship between individual land cover fractions and SEB fluxes is not clear because of interrelated effects of surface characteristics in the land cover mix. Daytime Bowen ratios vary inversely with vegetation fraction between and within cities for all weather scenarios. Impervious surface cover is positively correlated to the available energy that is partitioned into sensible heat. Cumulative evapotranspiration (ET) is similar for average weather conditions across medium wet sites in Phoenix and Portland but varies more in Portland than in Phoenix under extreme weather conditions. Results suggest that land cover manipulation could offset influences of weather extremes on ET in Portland to a certain degree but not in Phoenix. These findings highlight the importance of spatial and climatic context in the urban design process to mitigate the effects of urbanization. Copyright © 2011 Royal Meteorological Society

KEY WORDS urban climate; surface energy balance; vegetation; land cover; urban heat island; sensitivity analysis; LUMPS

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1. Introduction

Anthropogenic alterations of surface morphology due to urbanization significantly change the local surface energy balance (SEB) and create a new, local microclimate (Bonan, 2000; Harman and Belcher, 2006; Coutts *et al.*, 2007; Roth, 2007; Hart and Sailor, 2009; Pearlmutter *et al.*, 2009). In particular, anthropogenic land cover modifications alter net radiation, heat storage in the urban fabric, and the partitioning of the latent and sensible heat flux. Through urbanization, natural surfaces are replaced by materials with higher material heat capacity and thermal conductivity, different moisture characteristics, and different radiative properties (lower surface albedo and emissivity). The SEB is further influenced by increased surface area and roughness of urban form, the size, shape, and density of buildings and roads, urban canyon geometry, sky-view factor, distribution of green space, anthropogenic heat, and air

pollution (Christen and Vogt, 2004; Harman and Belcher, 2006; Stone and Norman, 2006; Hart and Sailor, 2009).

Urbanization leads to an urban heat island (UHI) effect, which is defined as a temperature increase of urban areas compared with surrounding rural sites. The UHI effect is more prominent at night and may negatively impact urban ecosystems, air quality, stream temperature, human comfort and health, and energy consumption for cooling (Golden, 2004; Harlan *et al.*, 2006; Brazel *et al.*, 2007). Mitigating heat islands is of paramount importance in urban areas, especially because UHI effects are locally of greater magnitude than projected global climate change effects and they increase the urban population's vulnerability to future global environmental change (Grimmond, 2007). Therefore, understanding the link between urbanization and microclimate is imperative for urban environmental planning to determine effective design strategies, e.g. altering the vegetation and irrigation regime, in order to improve urban climate. The knowledge of how to purposefully manipulate the SEB by changing urban land cover is crucial to urban climate adaptation.

* Correspondence to: Ariane Middel, Decision Center for a Desert City (DCDC), Arizona State University, PO Box 878209, Tempe, AZ 85287-8209, USA. E-mail: ariane.middel@asu.edu

Urban effects occur at different degrees of urban development and under different climate regimes, and their intensity varies spatially (Wienert and Kuttler, 2005; Offerle *et al.*, 2006; Hart and Sailor, 2009). Scalar energy fluxes of the SEB are influenced by the mix of land cover and heterogeneous morphology across the urban area. The SEB also varies with latitude, ambient meteorology, and distinct climates because urban microclimate is linked to regional and global climatic conditions. Consequently, urban design and land cover strategies have varying impacts on the SEB based on climate and therefore have to be understood and tailored to the climatic region of an urban area. This knowledge of relative contributions of recent climate variability and land cover in understanding the SEB of urban areas will be increasingly important in the 21st century, especially for cities in the South-west United States, where temperatures are predicted to increase due to climate change and rapid growth is expected (MacDonald, 2010). Thus, the objective of this study was to identify to what extent the SEB is controlled by current land cover and regional climate. Specifically, this paper asks (1) How does the mix of land cover affect the urban SEB under climate extremes and norms of two western US cities with distinct climates and what are the relative contributions of climate and variable land cover on the SEB? (2) How does the SEB vary due to land cover mix and, simultaneously, under historic extremes of climate experienced by the two cities? To address these questions, we use the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) model after Grimmond and Oke (2002). LUMPS has been shown to model fluxes in good agreement with observations (Grimmond and Oke, 2002; Masson *et al.*, 2002; Offerle *et al.*, 2006). Our study areas are located in Phoenix and Portland, two cities with distinct climates (desert and marine west coast, respectively). Although Phoenix, Arizona, and Portland, Oregon, differ in terms of location, climate regime, urban size, and development density, both cities exhibit a distinct UHI effect (Brazel *et al.*, 2000; Baker *et al.*, 2002; Hart and Sailor, 2009) and have dry summers when there is heavy demand for outdoor water use (Gober *et al.*, 2010). In Phoenix, UHI effects have already raised summer night-time temperatures by as much as 6 °C (Brazel *et al.*, 2000), which is comparable to the most pessimistic climate model results for the Southwestern United States (Gober *et al.*, 2010). In Portland, future population growth, expansion of the air-conditioning market, and global climate change may increase the summertime UHI effects (Hart and Sailor, 2009). We ran LUMPS for Phoenix and Portland for the driest months in summer – June for Phoenix and July for Portland. We investigated normal climate and recorded extremes in climatic conditions and analysed the partitioning and magnitude of the energy fluxes in the SEB for daytime situations. Running the model for different climates and intra-urban land cover mixes facilitates a sensitivity analysis of the relative impacts of local land cover variations and regional climate impacts on the SEB. The results can establish a basis of informed decision

making on alterations in land cover to mitigate effects of drought and heat extremes based on the potential impacts of climate change.

2. LUMPS model

LUMPS, developed by Grimmond and Oke (2002), simulates the SEB of urban areas at the local or neighborhood scale (0.01–100 km²). The model calculates the one-dimensional spatial and temporal variability in heat fluxes in the inertial sub-layer above the urban canopy's roughness sub-layer, where the micro-scale variability of atmospheric effects from the urban morphology is assumed to be integrated into a characteristic neighborhood response (Grimmond and Oke, 2002). The urban SEB modelled by LUMPS is driven by the net all-wave radiation $Q^* = Q_E + Q_H + \Delta Q_S$ (W·m⁻²), where Q_E and Q_H are the turbulent latent and sensible heat fluxes, respectively, and ΔQ_S is the heat storage. LUMPS incorporates several sub-models to solve the SEB equation. The turbulent fluxes of sensible and latent heat fluxes are partitioned from the available energy $Q^* - \Delta Q_S$ adopting an approach from Holtslag and Van Ulden (1983). The Objective Hysteresis Model (OHM) is an empirical model used to parameterize the heat storage ΔQ_S of the urban area from the net all-wave radiation Q^* and basic surface characteristics (Grimmond *et al.*, 1991; Grimmond and Oke, 1999b). Moreover, LUMPS implements the Net All-wave Radiation Parameterization to estimate Q^* from solar radiation (Offerle, 2003; Offerle *et al.*, 2003; Loridan *et al.*, 2010). Heat fluxes in LUMPS are modelled based on standard meteorological observations (air temperature, relative humidity, atmospheric pressure, and precipitation) and basic land cover characteristics (plan-area fractions of vegetation, buildings, impervious surfaces, soil, and water bodies).

The LUMPS model has been extensively tested using field observations from ten sites in seven North American cities with different urban forms and climate regimes (Grimmond *et al.*, 1991; Grimmond, 1992; Grimmond and Oke, 1995, 1999b, 2002). The parameterizations of Q_E and Q_H were evaluated in Vancouver (British Columbia, Canada), Chicago (Illinois), Miami (Florida), Los Angeles and Sacramento (California), Tucson (Arizona), and Mexico City (Mexico). LUMPS results were further evaluated using airborne hyperspectral imagery (Xu *et al.*, 2008). A more recent study evaluated LUMPS with observations from sites in Lodz, Poland, and Baltimore, Maryland (Loridan *et al.*, 2010). The multicity analyses confirm that LUMPS performs well in urban areas at a local scale; yet, the model has some limitations. First, since the model assumes a one-dimensional SEB, it does not perform well in areas with sharp land cover boundaries and mixed source areas, e.g. in coastal areas, at the rural–urban fringe or in complex mountainous terrain. Second, the anthropogenic heat flux Q_F is assumed to be implicitly included in the parameterization that was derived from field observations. Thus, the

observational base of the coefficient estimation is biased towards the conditions encountered at the model calibration sites, which are mainly in low-density residential areas. Loridan *et al.* (2010) showed errors for the fluxes as a function of air temperature, number of hours after a rain, wind direction, and wind speed. The Q_E values from LUMPS at midday were *ca.* $20 \text{ W}\cdot\text{m}^{-2}$ less than observed. LUMPS underestimates night-time Q_H and Q_E for low temperatures because the model attributes all of the available night-time energy deficit ($Q^* - \Delta Q_S$) to turbulent heat exchange and simulates large negative sensible and latent heat fluxes. Consequently, industrial areas and high-rise residential or commercial neighborhoods are not recommended for model use without an explicit representation of the anthropogenic heat flux. Third, the advection of heat and moisture is unaccounted for in LUMPS, since the model is assumed to be used at a local scale where micro-scale advection is inherent in the parameterization. Implicit modelling of anthropogenic heat flux and advection limits the performance of LUMPS but at the same time reduces input requirements and the complexity of the parameterization.

LUMPS has been intensively used to model the SEB in different climates (Offerle *et al.*, 2006; Gober *et al.*, 2010; House-Peters and Chang, 2011). Offerle *et al.* (2006) analysed the intra-urban spatial variability of energy partitioning across a Central European city with LUMPS to examine the correlation between heat flux partitioning and physical surface properties. The authors found that Bowen ratios (β ratio of sensible to latent heat fluxes) show an inverse relation with increasing vegetation cover, and sensible heat fluxes are positively correlated to built-up area. Gober *et al.* (2010) used LUMPS for investigating temperature variations and evapotranspiration (ET) in ten census tracts in central Phoenix under three land cover change scenarios and observed lower night-time temperatures with increased vegetation coverage. Their study was extended by analysing summertime atmospheric heating, cooling, and water use in 52 census tracts in the Phoenix urban core under different land cover scenarios. House-Peters and Chang, 2011 introduced the uncertainty of climate change to the land cover scenario-based SEB modelling. Their studies applied LUMPS to examine the effects of combined land cover and climate change scenarios on residential water use and night-time cooling in suburban Hillsboro, Oregon, and Phoenix, Arizona, respectively. Climate change was simulated by modifying model input temperatures according to IPCC (2007) projected trends.

The tradeoff between performance and complexity of urban parameterizations was identified for 33 different SEB models by Grimmond *et al.* (2010). Results suggest that LUMPS is sophisticated enough to simulate the temporal and spatial variability of urban heat fluxes at a neighborhood scale. Previous scenario-based research studies applying the LUMPS model have mainly focused on creating land cover scenarios and climate scenarios. However, past studies have not analysed systematically the relative contributions of local climate and land cover

to the SEB. While past climate change scenarios have primarily been created by modifying only temperature (Balling and Cubaque, 2009; House-Peters and Chang, 2011), other climate variables received less attention, such as variability of incoming solar radiation, a key driver for ET. Our study will close this gap and use LUMPS to investigate relative contributions of different climate variables and land cover on the SEB and to study the internal sensitivity of the model to important input parameters.

For analysing the effect of land cover and climate on the urban SEB, we use the current release version LUMPS 5.3 from Grimmond. In a significant improvement over previous releases, the implementation of a simple surface water balance allows for a better treatment of seasonal and synoptic weather conditions (Offerle, 2003).

3. LUMPS model validation

Past studies evaluated the LUMPS model (Grimmond and Oke, 1999a, 2002) based on the test of the OHM. This portion of the LUMPS model calculates the storage of heat flux ΔQ_S as it relates to net all-wave radiation Q^* and surface properties of a site. Grimmond and Oke (1999a,b) included an analysis of several cities from differing climate regimes and land cover. The OHM model performed well for hourly totals with root mean square error estimates of less than $80 \text{ W}\cdot\text{m}^{-2}$. In a later article (Grimmond and Oke, 2002), turbulent fluxes modelled in the overall LUMPS model were evaluated from various flux tower campaigns. In a series of comparisons of observed fluxes and LUMPS modelled fluxes, root mean square error values were less than $50 \text{ W}\cdot\text{m}^{-2}$. In absence of flux tower evaluations for the two study areas, we extracted past records from a number of publications addressing energy budget fluxes for the nearby cities of Tucson, to compare to Phoenix, and Vancouver, to compare with Portland. We chose summer conditions and developed Table I with data on land cover and parameters of the energy budget and ratios commonly shown in the past studies. For comparison, we chose census block groups in Phoenix and Portland that came closest to land cover fractions studied in Tucson and Vancouver. Data for Phoenix and Portland are LUMPS results; Tucson and Vancouver data are observations.

For the Phoenix–Tucson comparison, $\Delta Q_S/Q^*$ is higher for Phoenix and Q_E/Q^* and Q_H/Q^* are lower for Tucson. Similarly, the comparison of the Vancouver and Portland data shows that for Portland $\Delta Q_S/Q^*$ is considerably higher and as a result Q_E/Q^* and Q_H/Q^* are lower. However, absolute differences between Phoenix and Portland follow a comparable pattern to that between Tucson versus Vancouver, validating the use of LUMPS in comparing the two cities. These comparisons are similar to previous LUMPS model tests comparing *in situ* flux tower data and components of the LUMPS model ΔQ_S , Q_E , and Q_H (Grimmond and Oke, 1999a, 2002).

Comparing outdoor water use with LUMPS ET output, Gober *et al.* (2010) found that the outputs from

Table I. Validation of LUMPS model in Portland and Phoenix for daytime ($Q^* > 0$) (Grimmond and Oke, 1999a).

	Vancouver	Portland	Phoenix	Tucson
Buildings (%)	0.31	0.28	0.22	0.21
Impervious surfaces (%)	0.23	0.21	0.37	0.37
Unmanaged soil (%)	0.02	0.06	0.15	0.18
Trees (%)	0.09	0.16	0.12	0.12
Grass (%)	0.35	0.30	0.12	0.13
Water bodies (%)	0.00	0.00	0.02	0.01
Q^* (MJ m ⁻²)	12.08	12.65	17.17	16.27
Q_H (MJ m ⁻²)	6.31	5.60	7.32	7.54
Q_E (MJ m ⁻²)	4.27	3.58	3.37	4.11
ΔQ_S (MJ m ⁻²)	2.16	3.46	6.48	4.62
Q_H/Q_E	1.47	1.60	2.15	1.83
Q_S/Q^*	0.17	0.27	0.38	0.28
Q_E/Q^*	0.34	0.28	0.20	0.25
Q_H/Q^*	0.5	0.44	0.43	0.47

[Correction added April 2012 after original online publication: in Table I the units have been corrected from 'W m⁻²' to 'MJ m⁻²'.]

LUMPS were closely correlated with City of Phoenix water records for an initial analysis of ten census tracts ($r^2 = 0.89$), indicating that the model produces credible estimates of outdoor water use. A more detailed assessment of 52 census tracts in Phoenix resulted in an r^2 of 0.77 between June 2007 ET and outdoor water use data. For selected Portland neighborhoods, House-Peters and Chang, 2011 report comparisons of LUMPS to observe outdoor water use that resulted in r^2 values ranging from 0.87 to 0.93. These comparisons, however, are biased with uncertainties related to the water use data and the model. Although data provide 'monthly' water consumption, these data may not be entirely synchronous with the climatic inputs. The r^2 statistics cited above are deceiving because the regression equation slope (water use x-axis vs LUMPS y-axis) differs from 1.0, with overestimates from LUMPS for low water use and underestimates at high water use. This corroborates the LUMPS versus observation comparison of Loridan *et al.* (2010) for Q_E .

4. Study sites

The City of Phoenix is the largest city and the capital of the state of Arizona with approximately 1.6 million people (U.S. Census Bureau, 2010), ranking it the fifth most populous city in the United States. Phoenix encompasses 1345.7 km² of land (City of Phoenix, 2010), of which only 0.05% is surface water, and has a low population density of about 1200 people per square kilometer. Phoenix is located at 33°29'N, 112°4'W in the northeastern reaches of the Sonoran Desert (Figure 1). The city lies at a mean elevation of 340 m in the center of the dry Salt River Valley, a nearly flat plain also known as the Valley of the Sun.

Typical of the Arizona desert, Phoenix has an arid climate with extremely hot summers and mild winters.

With an annual average of 85% of possible sunshine and mean high temperatures over 39.9°C throughout the summer months (Table II), the Phoenix climate is among the hottest of any major city in the United States. July is the warmest month of the year with a mean maximum temperature of 41.4°C. Summer overnight lows average 24.2°C in June and exceed 27°C in July and August. Winter months feature mean daily high temperatures above 13°C and low temperatures rarely below 4°C. Phoenix precipitation is considered low. The city receives an annual average rainfall of 210 mm with March being the wettest month (mean, 27.2 mm) and June being the driest (mean, 2.3 mm). The first of the two rainy seasons in Phoenix occurs between November and March when occasional winter storm systems from the Pacific Ocean move inland to Arizona. The second, the annual Arizona monsoon, begins in early July and extends through mid-September. A shift in the prevailing winds from the west and northwest to the south and southeast brings monsoonal moisture to Arizona from the Gulf of Mexico and the Gulf of California. The moisture influx increases humidity, thunderstorm activity, and can precipitate heavy rainfall and flooding. The highest mean daily precipitation in Phoenix occurs in July and August with monthly averages of over 23 mm.

The City of Portland is situated at 45°31'N, 122°41'W in the Pacific Northwest region of the United States near the confluence of the Columbia and Willamette River (Figure 1). Portland is the largest city in the state of Oregon with an estimated population of 566, 141 (U.S. Census Bureau, 2010), ranking it the 30th most populous city in the United States. The city has a total land area of 347.1 km² and an urban population density of about 1600 people per square kilometer. Portland is located about 100 km inland from the Pacific Ocean in a valley enclosed by the Oregon Coast Range to the west and the Cascade Mountain Range to the east, each at about 50 km distance from the city centre.

Portland experiences a temperate but varied climate, which is strongly influenced by the Pacific Ocean. Portland's oceanic or marine west coast climate is characterized by warm, relatively dry summers and mild, rainy winters. With an annual average of 48% of possible sunshine, Portland records on average 155 d with measurable rainfall. Almost 90% of the total annual precipitation, which amounts to 941.6 mm (Table III) occurs between October and May. July is the driest month with a mean precipitation of 18.3 mm. Summer temperatures reach an average high of above 26°C in July and August and a low around 14°C. The winter season is mild to cold with changeable, rainy, or cloudy weather and mean maximum temperatures of approximately 7°C in January and February.

5. Methodology

For our analysis, we focused on June for Phoenix and July for Portland because these were the driest months of

Figure 1. Study sites in Phoenix, Arizona, and Portland, Oregon.

Table II. Phoenix Weather Service Forecast Office (WSFO), Arizona, National Climatic Data Center (NCDC) 1971–2000 monthly normals (Western Regional Climate Center, 2010).

	January	February	March	April	May	June	July	August	September	October	November	December
Mean maximum temperature (°C)	19.6	21.9	24.5	29.3	34.4	39.9	41.4	40.3	37.2	30.9	23.9	19.5
Mean temperature (°C)	13.4	15.5	18.1	21.8	27.1	32.1	34.9	33.9	30.7	23.8	17.1	13.1
Mean minimum temperature (°C)	7.1	9.1	11.7	14.2	19.7	24.2	28.3	27.6	24.2	16.7	10.2	6.6
Mean precipitation (mm)	21.1	19.6	27.2	6.4	4.1	2.3	25.1	23.9	19.1	20.1	18.5	23.4
Highest precipitation (mm)	132.6	74.4	80.5	28.7	26.9	43.2	130.8	88.9	85.3	111.8	70.9	78.2
Lowest precipitation (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

the year in both locations (Tables II and III) and therefore best comparable. We examined normal climate conditions (base-case) averaged for the past 11 years (1999–2009) and extreme weather conditions (maximum and minimum temperatures and incoming solar radiation) recorded over the past 40 years (1970–2009). Normalized heat fluxes and heat partitioning in the SEB were calculated using the LUMPS model. The spatial unit of analysis was the census block group (typical size 0.5 km²). Compared with

previous studies, which investigated census tracts (Gober *et al.*, 2010), census block groups are more homogeneous and have less abrupt changes in surface characteristics. We chose approximately 200 census block groups in both Phoenix and Portland that constitute a representative cross-section of the urban landscape (Figure 1). Study areas in each city include the downtown district as well as neighborhoods around the city centre with varying degrees of development and population density.

Table III. Portland Weather Service Forecast Office, Oregon, National Climatic Data Center 1971–2000 monthly normals (Western Regional Climate Center, 2010).

	January	February	March	April	May	June	July	August	September	October	November	December
Mean maximum temperature (°C)	7.6	10.2	13.2	15.8	19.3	22.6	26.3	26.5	23.7	17.4	11.0	7.4
Mean temperature (°C)	4.4	6.2	8.4	10.7	13.9	17.1	20.1	20.3	17.6	12.4	7.7	4.6
Mean minimum temperature (°C)	1.2	2.2	3.7	5.5	8.6	11.4	13.8	14.1	11.4	7.3	4.3	1.7
Mean precipitation (mm)	128.8	106.2	94.2	67.1	60.5	40.4	18.3	23.6	41.9	73.2	142.5	145.0
Highest precipitation (mm)	216.2	254.8	181.4	133.6	141.0	103.1	68.1	83.6	109.2	213.6	293.4	339.1
Lowest precipitation (mm)	1.5	18.3	37.8	26.4	2.5	3.6	0.0	0.0	0.0	4.8	19.6	35.1

The Phoenix study area comprises 201 contiguous census block groups and is located in and around the urban core. Some neighborhoods have commercial or industrial character with a high percentage of impervious land cover and little vegetation, but most block groups have primarily residential urban land uses with moderately moist (mesic) or low water use (xeric) landscaping. For Portland, we selected a study area with a total of 220 census block groups, covering the downtown and surrounding business and industrial districts by the Willamette River, low-density residential areas with high percentages of canopy trees and patches of woods, and mixed development areas with some combination of commercial and residential areas containing both mesic and xeric landscaping.

5.1. Determination of land cover

For the Phoenix study area, we derived the six land cover classes required by the LUMPS model from Quickbird 2.4 m spatial resolution imagery acquired on May 29, 2007, with an object-oriented image classification approach introduced by Myint *et al.* (2011). The average land cover fractions for the 201 census block groups under investigation were computed at block group level. To minimize location errors between the land cover map generated from the Quickbird image and the administrative boundary map (i.e. census block group), we coregistered both datasets. We then overlaid both maps to extract land cover fractions at the block group level.

For the Portland study area, we obtained GeoEye-1 satellite imagery, acquired on August 19, 2009, with a spatial resolution of 2.5 m. The images were classified adopting an object-oriented approach presented by Myint *et al.* (2008a, 2008b) and modified by House-Peters and Chang, 2011. The classification scheme used the four spectral bands of the image, the normalized difference vegetation index, the components from principal component analysis, and light detection and ranging feature

height data to extract land cover fractions for each of the 220 census block groups in the Portland study area. Similar to the process used in the Phoenix area, we summarized the block group level land cover fractions from the land cover maps classified on the satellite imagery. The areas of the GeoEye-1 image obscured by building or tree shadows were classified originally as ‘unknown’, but during the calculation of land cover fractions, they were assigned to building or tree fractions in proportion to those fractions classified in the block groups. The area of the Willamette River near downtown Portland was excluded from the calculation to avoid an abrupt change in land cover, which violates the first LUMPS assumption (see Section 2).

5.2. Weather data

To calculate the SEB from land cover, LUMPS requires hourly meteorological observations of air temperature, relative humidity, solar radiation, precipitation, and air pressure. We used the regionally available representative weather files as a first approximation to generate LUMPS energy budget estimates, as no flux tower data exist in either of the two cities for our use. The weather files were not adjusted to a flux tower equivalent height nor were the data adjusted in any way to each block group. We selected the months June (Phoenix) and July (Portland) for our comparative summertime analysis of urban heat fluxes and acquired hourly data from a representative weather station in each study area. For Phoenix, we retrieved meteorological observations from an Arizona Meteorological Network (AZMET, 2010) station located within the mid-western part of the study area. For the Portland area, we obtained weather data of the PDX International Airport from the Western Regional Climate Center and solar radiation data from the University of Oregon Solar Radiation Monitoring Laboratory. We averaged the hourly meteorological observations in both cities for June (Phoenix) and July (Portland) over the years 1999–2009

Table IV. Descriptive comparison of land cover characteristics for study areas in Phoenix and Portland.

	Phoenix ($N = 201$)		Portland ($N = 220$)		t -Statistic	Significance	Mean difference
	Mean	σ	Mean	σ			
% Buildings	0.206	0.046	0.236	0.078	-4.725	0.000	-0.0300
% Impervious	0.265	0.100	0.243	0.086	2.323	0.021	0.0211
% Soil	0.184	0.073	0.015	0.019	33.079	0.000	0.1691
% Trees	0.112	0.054	0.320	0.132	-20.826	0.000	-0.2080
% Grass	0.230	0.103	0.185	0.069	5.265	0.000	0.0446
% Water	0.004	0.005	0.001	0.002	8.149	0.000	0.0032
% Wet fraction	0.345	0.149	0.505	0.147	-11.118	0.000	-0.1602
% Hard surfaces	0.471	0.119	0.480	0.143	-0.695	0.488	-0.0090

Figure 2. Land cover mix in Phoenix and Portland.

to represent typical summer conditions. Incoming solar radiation for Portland was only averaged for the years 2005–2009 since earlier observations were unavailable. To analyse relative climate variability at the two urban areas, we accessed solar archived data from the National Solar Radiation Data Base (NSRDB, 2010) and past records of the Phoenix AZMET data base and National Oceanic and Atmospheric Administration (NOAA) data from Portland. These data were used to construct Table VI, depicting not only land cover variations but also weather variability. We created three weather scenarios: (1) base-case, an 11-year (1999–2009) average of hourly meteorological observations for June (Phoenix) and July (Portland) representing current local climate conditions; (2) maximum weather scenario, representing the upper limit of daily temperature and solar radiation variations in June/July in the past 40 years (1970–2009); and (3) minimum weather scenario, representing the lower limit of daily temperature and solar radiation variations in June/July in the past 40 years (1970–2009).

6. Results

6.1. Land cover analysis

The selected study areas in Phoenix and Portland differ widely in land cover. The mean values of land cover types

for both study areas are summarized in Table IV. These values do not represent a city-wide assessment of land cover but describe the typical surface characteristics of the built-up inner core in both cities, where UHI mitigation might be considered important (personal communication, Phoenix Water Services Department). On average, the selected area in Portland encompasses more buildings, but block groups in Phoenix have more impervious surfaces. These two categories offset each other and result in a similarly high percentage of hard surfaces (aggregation of buildings and impervious fraction), suggesting a comparable urbanization grade. Other surface type fractions vary significantly. On average, the Phoenix study area has more water bodies than Portland, which can be attributed to a higher number of swimming pools in Phoenix. Phoenix block groups average 17% more soil than block groups in Portland (Figure 2(a)). Soil is Phoenix's natural desert landscape, predominant on vacant lots, and used for xeric landscaping. In contrast, Portland's block groups have 16% more wet fraction (aggregated fractions of trees and shrubs, grass, and water bodies) than those in Phoenix. Particularly, Portland exhibits a significantly higher percentage of trees, as mild temperatures and plentiful rainfall expedite tree growth in this area. While trees grow naturally in Portland, most of Phoenix's wet

Figure 3. Controlled (irrigated) landscaping in Phoenix (a) versus uncontrolled landscaping in Portland (b). In Phoenix, the amount of grass increases linearly with the amount of trees. In Portland, trees grow naturally without irrigation, therefore, tree fractions vary widely with increasing grass fraction.

fraction is established through controlled irrigated landscaping (Figure 3). Due to the arid climate in Phoenix, non-native trees, shrubs, and lawn will not grow without some form of irrigation. In Phoenix, the amount of grass and trees increases almost linearly. Most landscaping in the study area incorporates both trees and grass into the design, and although the percentage of grass in the wet fraction is higher, both grass and trees seem to increase at the same rate. The land cover mix in Portland does not exhibit a clear relationship between the amount of trees and grass. Tree fractions vary widely with increasing grass fraction. Trees in Portland do not require irrigation, they grow naturally and populate empty lots, similar to soil and shrubs in Phoenix.

From Figures 2 and 3, we conclude that analysing the impact of distinct LUMPS input surface characteristics on the modelled SEB is not recommended for two reasons: (1) all land cover fractions are correlated, since they add up to one and (2) the relationship between individual land cover fractions and SEB fluxes or climate variables will not be clear, especially for sites with uncontrolled land cover, because the correlation is distorted by other land cover fractions in the mix (e.g. correlating two sites of identical grass fraction with latent heat fluxes at these sites might result in different relationships because other land cover fractions in the mix influence the SEB as well). These findings agree with the interrelated effects of different surface characteristics previously identified by several studies. Shashua-Bar (2011) found that the actual microclimatic effects of vegetation are complex and interrelated with the effects of other built environments. Oke *et al.* (1999) noted that typically, the sensible heat flux is likely to increase with impervious land cover, but at the same time, the relationship is influenced by water availability and the efficiency of storage.

6.2. Analysis of energy partitioning

Here, we summarize the most important characteristics of the SEB for selected sites, focusing on flux partitioning, the magnitude of fluxes, and their variability under

different weather extremes. We analyse the variability of energy partitioning for daytime situations. LUMPS output includes net radiation flux density Q^* , sensible heat flux density Q_H , latent heat flux density Q_E , and the storage heat flux ΔQ_S , which is determined as energy balance residual. To remove the effects of varying energy available for partitioning (Q^* is generally higher in Phoenix than in Portland and varies across weather extremes), daytime fluxes are normalized by net all-wave radiation. This allows for a direct comparison of flux partitioning trends between the two cities and across weather scenarios. Basically, the flux ratio $\chi = Q_H/Q^*$ denotes how much available energy is dissipated to warm the air, $\gamma = Q_E/Q^*$ represents the amount of energy used to dry the source-area surface, and $\Lambda = \Delta Q_S/Q^*$ is the available energy stored in the urban fabric. Flux totals and ratios of the daytime ($Q^* > 0$) energy balance, averaged daily over June for Phoenix and July for Portland, are presented in Table VI. Results are arranged in a matrix with the base-case and two extreme weather scenarios for a dry, medium wet, and wet site in each city. Corresponding land cover fractions for the six sites are listed in Table V.

Flux totals and ratios in Table VI show that the SEB varies spatially within and across the two cities. Variability is least for the sensible heat flux Q_H and greatest for the latent heat flux Q_E across all sites and weather extremes. Daytime Q_H is greater than Q_E for the dry to medium wet block groups in both cities for all weather scenarios. In these block groups, the reduced Q_E is offset by increased values for ΔQ_S and Q_H . The sensible heat flux becomes the most important heat sink in the SEB with 45–59% of the daytime Q^* . However, in the highly vegetated block groups, Q_E is the most significant energy loss and constitutes an energy sink of 42–49% of the daytime Q^* , which is on average a 32% increase compared with dry sites. These trends are in agreement with the results of Pearlmutter *et al.* (2009), who found that local landscape irrigation leads

Table V. Land cover fractions for dry, medium wet, and wet block groups in Phoenix and Portland.

	Buildings	Impervious	Soil	Trees	Grass	Water
Phoenix						
Wet	0.1494	0.1069	0.0704	0.2713	0.3946	0.0073
Medium wet	0.2182	0.1828	0.2633	0.0932	0.2421	0.0003
Dry	0.2742	0.5366	0.1718	0.0108	0.0067	0.0000
Portland						
Wet	0.0601	0.0871	0.0018	0.6455	0.1956	0.0099
Medium wet	0.2650	0.2415	0.0015	0.3281	0.1640	0.0000
Dry	0.5453	0.3031	0.0082	0.1197	0.0238	0.0000

Table VI. Summarized daytime ($Q^* > 0$) energy fluxes and flux ratios averaged over 30 (31) d in June (July) for Phoenix (Portland) for base-case and extreme weather variability scenarios.

	Q^*	Q_H	Q_E	ΔQ_S	χ	γ	Λ	β	ET	$Q_H/(Q^* - \Delta Q_S)$
Phoenix										
Base-case (wet)	16.340	5.683	6.934	3.723	0.348	0.424	0.228	0.820	3.055	0.450
Base-case (med.)	15.993	7.390	4.155	4.448	0.462	0.260	0.278	1.778	1.830	0.640
Base-case (dry)	16.457	7.933	1.774	6.750	0.482	0.108	0.410	4.472	0.781	0.817
Maximum (wet)	17.499	5.966	7.455	4.077	0.341	0.426	0.233	0.800	3.284	0.445
Maximum (med.)	17.133	7.805	4.455	4.873	0.456	0.260	0.284	1.752	1.963	0.637
Maximum (dry)	17.623	8.385	1.889	7.349	0.476	0.107	0.417	4.438	0.832	0.816
Minimum (wet)	14.557	5.290	6.107	3.159	0.363	0.420	0.217	0.866	2.691	0.464
Minimum (med.)	14.238	6.783	3.679	3.777	0.476	0.258	0.265	1.844	1.621	0.648
Minimum (dry)	14.664	7.263	1.591	5.811	0.495	0.108	0.396	4.566	0.701	0.820
Portland										
Base-case (wet)	14.152	5.216	6.874	2.062	0.369	0.486	0.146	0.759	3.028	0.431
Base-case (med.)	13.759	6.363	4.175	3.221	0.462	0.303	0.234	1.524	1.839	0.604
Base-case (dry)	13.365	7.497	2.223	3.646	0.561	0.166	0.273	3.373	0.979	0.771
Maximum (wet)	16.994	5.951	8.357	2.686	0.350	0.492	0.158	0.712	3.681	0.416
Maximum (med.)	16.539	7.371	5.035	4.132	0.446	0.304	0.250	1.464	2.218	0.594
Maximum (dry)	16.083	8.765	2.658	4.659	0.545	0.165	0.290	3.297	1.171	0.767
Minimum (wet)	10.920	4.279	5.288	1.353	0.392	0.484	0.124	0.809	2.330	0.447
Minimum (med.)	10.606	5.162	3.254	2.190	0.487	0.307	0.206	1.586	1.434	0.613
Minimum (dry)	10.291	6.035	1.755	2.501	0.586	0.171	0.243	3.438	0.773	0.775

Energy fluxes in $\text{MJ}\cdot\text{m}^{-2}$: Q^* , net radiation flux density; Q_H , sensible heat flux density; Q_E , latent heat flux density; ΔQ_S , storage heat flux density; flux ratios $\chi = Q_H/Q^*$, $\gamma = Q_E/Q^*$, $\Lambda = \Delta Q_S/Q^*$, $\beta = Q_H/Q_E$ (Bowen ratio), $Q_H/(Q^* - \Delta Q_S)$ are non-dimensional; cumulative daytime ET in millimetres. Mean daily inputs of base-case, maximum, and minimum climate data: Phoenix, 31.2, 32.6, and 28 °C for temp (representing +4.4 and −10.3% from mean) and 338.8, 370.4, and 310.8 $\text{W}\cdot\text{m}^{-2}$ for incoming solar radiation (representing +9.3 and −8.3% from mean); Portland, 20.4, 22.5, and 18.4 °C (representing +10.3 and −9.8% from mean); 256.3, 264.6, and 242.8 $\text{W}\cdot\text{m}^{-2}$ (representing +4.5 and −5.3% from mean).

to a substantial daytime latent heat contribution in arid regions.

During the day, surface wetness (determined by vegetation cover and water availability) drives the relative partitioning of Q_H and Q_E , which is also reflected in the average daytime Bowen ratio for all weather scenarios in Phoenix and Portland ($\beta < 0$ at wet sites, $\beta > 0$ at medium wet and dry sites). Notably, block groups characterized by large (low) vegetative cover have the largest (lowest) γ ratios across weather extremes in both cities. This inverse relationship is in line with Roth's finding that Q_E is related to vegetated area irrespective of climate (Roth, 2007). Furthermore, total daytime ΔQ_S is generally larger at dry sites than medium wet or wet sites, thus low vegetation cover promotes energy conduction into the

ground. This process is more pronounced in Phoenix than Portland, suggesting that ΔQ_S is sensitive to climate. χ is relatively constant amongst the dry and medium wet sites in Phoenix for all scenarios, but the dry site experiences a 13% increased heat storage uptake Λ compared with the wet site at the expense of Q_E .

Daytime Bowen ratios are typically higher in Phoenix than Portland due to a higher proportion of sensible heating proportional to latent heating in desert environments. The relation between source-area vegetation fraction and observed Bowen ratio for block groups in both cities is illustrated in Figure 4(a). Bowen ratios vary inversely with vegetation fraction between and within cities. At the same time, the ratio of Q_H to available energy is positively correlated with impervious surface cover

Figure 4. Average daytime Bowen ratio β as a function of source-area wet fraction (a), sensible heat available energy ratio $Q_H/(Q^* - \Delta Q_s)$ as a function of source-area impervious fraction (b).

(Figure 4(b)). These results show good agreement with a wide range of urban observations (Grimmond and Oke, 2002) and previous findings reported by Christen and Vogt (2004).

In LUMPS, the latent heat flux Q_E directly corresponds to the hourly ET rate measured in millimetres per hour. Figure 5 illustrates the cumulative daytime ET for the block groups and scenarios listed in Table VI. Values at the end of the graphs equal daytime estimates of ET shown in Table VI. Cumulative daytime ET is similar for average weather conditions across medium wet to wet sites in Phoenix and Portland. Dry sites in Phoenix have an overall lower ET. Typically, dry sites are less sensitive to weather variations than wet sites in both cities. Under extreme weather conditions, ET values vary more in Portland (Figure 5(b)) than in Phoenix (Figure 5(a)). Results indicate that land cover manipulation could in fact offset influences of deleterious weather extremes on ET in Portland to a certain degree but not in Phoenix. Consequently, land cover strategies will have a different impact on the SEB under different climates. Our results confirm findings of previous studies showing that the spatial context of land cover strategies is important and that planning strategies have to be designed appropriate to the climatic region and to the related urban environment (Shashua-Bar *et al.*, 2009; Gober *et al.*, 2010).

6.3. Sensitivity analysis of climate inputs

Past scenario-based research studies on the relationship of land cover and climate primarily implemented temperature change to model future climate conditions as predicted by IPCC models (Balling and Cubaque, 2009; House-Peters and Chang, 2011). Other climate variables have received much less attention. In order to test the sensitivity of LUMPS to temperature and incoming solar radiation, we ran the maximum extreme weather scenario twice for Phoenix and Portland, first with increased temperatures only, then with only increased incoming solar radiation. The mean daytime flux differences between base-case and extreme weather scenarios where one climate variable was changed at a time are summarized

Figure 5. Cumulative daytime ET (millimetres) for base-case and weather extremes; for each scenario, ET is shown for wet, medium wet, and dry block groups in Phoenix (a) and Portland (b).

in Table VII. Results show that LUMPS is much more sensitive to changes in incoming solar radiation than to temperature variations. Note from Table VII that temperature only accounts for a small fraction of SEB fluxes (maximum: $0.09 \text{ MJ}\cdot\text{m}^{-2}$ in Phoenix and $0.29 \text{ MJ}\cdot\text{m}^{-2}$ in Portland), whereas incoming solar radiation accounts for up to $1.2 \text{ MJ}\cdot\text{m}^{-2}$ (Q^*) in Phoenix and $2.7 \text{ MJ}\cdot\text{m}^{-2}$ (Q^*)

Table VII. Flux differences (in MJ m⁻² for $Q^* > 0$) between base-case and maximum weather scenarios where only temperature or incoming solar radiation was manipulated.

Difference (base-case - maximum weather scenario)	Phoenix				Portland			
	Q^*	Q_H	Q_E	ΔQ_S	Q^*	Q_H	Q_E	ΔQ_S
Maximum temperature (wet)	-0.010	-0.088	0.081	-0.003	0.164	-0.160	0.287	0.036
Maximum temperature (medium wet)	-0.010	-0.054	0.048	-0.004	0.164	-0.060	0.170	0.054
Maximum temperature (dry)	-0.010	-0.024	0.019	-0.005	0.164	0.016	0.087	0.061
Maximum incoming solar radiation (wet)	1.169	0.376	0.435	0.358	2.678	0.932	1.158	0.588
Maximum incoming solar radiation (medium wet)	1.150	0.473	0.250	0.428	2.616	1.091	0.668	0.857
Maximum incoming solar radiation (dry)	1.175	0.477	0.095	0.604	2.554	1.265	0.337	0.952

in Portland. Incoming solar radiation not only drives Q^* but also influences how fluxes are partitioned. These findings indicate that it is advisable to include, if available, estimates of incoming solar radiation in climate scenarios when using energy budget models like LUMPS to better represent meteorological conditions.

7. Discussion and conclusions

This study investigated how land cover mix influences the SEB under weather norms and extremes in Phoenix and Portland, two cities in the western United States with distinct climates. Major differences in the intra-urban land cover mix between study sites in Phoenix and Portland revealed that it is important to analyse a mix of surface characteristics, not individual fractions whose effects on the SEB are interrelated. To analyse relative contributions of climate and variable land cover to the SEB, we examined daytime energy fluxes and energy flux partitioning within sites in each city and between cities for base case and extreme weather conditions. Each of the modelled fluxes varied both spatially and within climate extremes. In both cities, energy partitioning was mainly driven by moisture availability at the surface. Bowen ratios were inversely related to wet fraction, and the available energy partitioned into sensible heat was positively correlated with impervious surfaces. The normalized latent heat flux in the SEB increased with wet fraction, suggesting that vegetation can be used to reduce ΔQ_S and therefore mitigate the UHI effect. These findings are in agreement with other urban studies. However, we found cumulative daytime ET in Portland to be more sensitive to climate variability than in Phoenix. Significant intra-urban differences of cumulative daytime ET between wet and dry sites could even offset the effect of weather extremes in Portland to a certain degree but not in Phoenix. These findings clearly indicate that land cover strategies have a different impact on the SEB in different locations and under different climates.

A sensitivity analysis of climate variables required by LUMPS showed that incoming solar radiation is an important driver of the modeled SEB. Results suggest that when using LUMPS, estimates of solar radiation should be included in climate scenario runs to generate adequate outcomes rather than merely changing the air

temperature. Brazel *et al.* (1993) developed scenarios of Southwest United States solar receipt from four Global Circulation Model (GCM) runs for doubled CO₂. Results indicate 2–6% increases on annual basis, but for summer (JJA) a range among models of -6 to +17%. With respect to future climate change, Pan *et al.* (2004) show a possible 4% increase in incoming solar radiation for the Portland area for summer 2040 (JJA) and 4% decrease for Phoenix, mainly as a function of monsoon changes in July and August. In more recent downscaling and modelling efforts, Salathe *et al.* (2007) suggest Portland summer precipitation may decline slightly, which is consistent with the direction of change indicated by Pan *et al.* (2004) for incoming solar radiation. Bresson and Laprise (2011) explicitly produce scenarios of the water budget by winter and summer seasons (DJF and JJA) in their use of the Canadian Regional Climate Model for North America in which regional ET is mapped for changes from 1961–1990 to 2041–2071. Interpolating for the Pacific Northwest near Portland and for the Southwest United States near Phoenix from their Figure 13 (showing JJA projected differences), changes consistent with Pan *et al.* (2004) and Salathe *et al.* (2007) interpretations are noted with very little ET increases for Portland and some decreases in ET for summer in Phoenix (again for the combined JJA period). Thus, it is possible that by 2040, our minimum estimates for solar radiation may be appropriate for Phoenix and maximum estimates appropriate for Portland as a scenario to consider from the results of Table VI.

Local effects of pollution on solar radiation in the urban area compared with rural environments may also be significant in scenario constructs. For Phoenix, Suckling and Brazel (2010) report average aerosol-induced reductions in solar radiation of 4% between the city core and rural areas outside the city. This reduction has a magnitude similar to that of the projected magnitudes of future climate scenarios mentioned above. However, considerable analysis of future scenarios, not only of incoming solar radiation but also of temperature and precipitation, should be evaluated.

We acknowledge that our modelling approach has some limitations. First, we do not explicitly model the anthropogenic heat flux, which is assumed to be implicitly included in the LUMPS parameterization and

biased towards low-density residential areas. Most of the study sites in Phoenix meet this assumption, but the study area in Portland contains some areas of high density. To lower the error introduced by the anthropogenic heat flux, we restricted our analysis to daytime, as results would be particularly biased at night. Second, the weather files we used as model input represent hourly meteorological observations on the ground, not at flux tower height (35 m), where LUMPS was parameterized. Above-canopy observations are currently not available to us due to the lack of flux tower data for Portland and Phoenix. As a result, we had to rely on a comparison of our modelling results with previous field campaigns in Tucson and Vancouver for validation, which shows good agreement. More in depth comparisons are required, as well as tests against flux tower data. In Phoenix, a new flux tower is positioned in a neighborhood near the downtown area and a full evaluation of LUMPS will be made in the near future. Nevertheless, our results highlight the benefits of using a parameterized model to determine the relative impact of land cover and climate variations on the SEB. Our findings can form the basis for a better understanding of the LUMPS model sensitivity and its use in urban design to make better informed decisions on land cover strategies for mitigating urban effects.

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References

Baker LA, Brazel AJ, Selover N, Martin C, McIntyre N, Steiner FR, Nelson A, Musacchio L. 2002. Urbanization and warming of Phoenix (Arizona, USA): impacts, feedbacks and mitigation. *Urban Ecosystems* **6**: 183–203, DOI: 10.1023/A:1026101528700.

Balling RC Jr, Cubaque HC. 2009. Estimating future residential water consumption in Phoenix, Arizona based on simulated changes in climate. *Physical Geography* **30**: 308–323, DOI: 10.2747/0272-3646.30.4.308.

Bonan GB. 2000. The microclimates of a suburban Colorado (USA) landscape and implications for planning and design. *Landscape and Urban Planning* **49**: 97–114, DOI: 10.1016/S0169-2046(00)00071-2.

Brazel AJ, McCabe GJ Jr, Verville HJ. 1993. Incident solar radiation simulated by general circulation models for the southwestern United States. *Climate Research* **2**: 177–181.

Brazel AJ, Selover N, Vose R, Heisler G. 2000. The tale of two cities: Phoenix and Baltimore urban LTERs. *Climate Research* **15**: 123–135, DOI: 10.3354/cr015123.

Brazel AJ, Gober P, Lee SH, Grossman-Clarke S, Zehnder J, Hedquist B, Comparri E. 2007. Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research* **33**: 171–182, DOI:10.3354/cr033171.

Bresson R, Laprise R. 2011. Scale-decomposed atmospheric water budget over North America as simulated by the Canadian Regional Climate Model for current and future climates. *Climate Dynamics* **36**: 365–384, DOI: 10.1007/s00382-009-0695-4.

Christen A, Vogt R. 2004. Energy and radiation balance of a central European city. *International Journal of Climatology* **24**: 1395–1421, DOI: 10.1002/joc.1074.

City of Phoenix. 2010. *Community trends and profile*. 2009 [cited December 21 2010]. Available at <http://phoenix.gov/>.

Coutts AM, Beringer J, Tapper NJ. 2007. Impact of increasing urban density on local climate: spatial and temporal variations in the surface energy balance in Melbourne, Australia. *Journal of Applied Meteorology and Climatology* **46**: 477–493, DOI: 10.1175/JAM2462.1.

Gober P, Brazel A, Quay R, Myint S, Grossman-Clarke S, Miller A, Rossi S. 2010. Using watered landscapes to manipulate urban heat island effects. *Journal of the American Planning Association* **76**: 109–121, DOI: 10.1080/01944360903433113.

Golden JS. 2004. The built environment induced urban heat island effect in rapidly urbanizing arid regions – a sustainable urban engineering complexity. *Journal of Integrative Environmental Sciences* **1**: 321–349, DOI: 10.1080/15693430412331291698.

Grimmond CSB. 1992. The suburban energy balance: methodological considerations and results for a mid-latitude west coast city under winter and spring conditions. *International Journal of Climatology* **12**: 481–497, DOI: 10.1002/joc.3370120506.

Grimmond CSB. 2007. Urbanization and global environmental change: local effects of urban warming. *Geographical Journal* **173**: 83–88, DOI: 10.1111/j.1475-4959.2007.232.3.x.

Grimmond CSB, Oke TR. 1995. Comparison of heat fluxes from summertime observations in the suburbs of four North American cities. *Journal of Applied Meteorology* **34**: 873–889, DOI: 10.1175/1520-0450(1995)034<0873:COHFFS>2.0.CO;2.

Grimmond CSB, Oke TR. 1999a. Evapotranspiration rates in urban areas. In *Impacts of Urban Growth on Surface Water and Groundwater Quality, Proceedings of IUGG 99 Symposium H55*. IAHS Pub: Birmingham, 259.

Grimmond CSB, Oke TR. 1999b. Heat storage in urban areas: local-scale observations and evaluation of a simple model. *Journal of Applied Meteorology* **38**: 922–940, DOI: 10.1175/1520-0450(1999)038<0922:HSIUAL>2.0.CO;2.

Grimmond CSB, Oke TR. 2002. Turbulent heat fluxes in urban areas: observations and a local-scale urban meteorological parameterization scheme (LUMPS). *Journal of Applied Meteorology* **41**: 792–810, DOI: 10.1175/1520-0450(2002)041<0792:THFIUA>2.0.CO;2.

Grimmond CSB, Cleugh HA, Oke TR. 1991. An objective urban heat storage model and its comparison with other schemes. *Atmospheric Environment* **25B**: 311–326, DOI: 10.1016/0957-1272(91)90003-W.

Grimmond CSB, Blackett M, Best MJ, Barlow J, Baik JJ, Belcher SE, Bohnenstengel SI, Calmet I, Chen F, Dandou A, Fortuniak K, Glouvea ML, Hamdi R, Hendry M, Kawai T, Kawamoto Y, Kondo H, Kravynhoff ES, Lee SH, Loidan T, Martilli A, Masson V, Miao S, Oleson K, Pigeon G, Porson A, Ryu YH, Salamanca F, Shashua-Bar L, Steeneveld GJ, Tombrou M, Voogt J, Young D, Yhang N. 2010. The international urban energy balance models comparison project: first results from phase 1. *Journal of Applied Meteorology and Climatology* **49**: 1268–1292, DOI: 10.1175/2010JAMC2354.1.

Harlan S, Brazel AJ, Prashada L, Stefanov WL, Larsen L. 2006. Neighborhood microclimates and vulnerability to heat stress. *Social Sciences & Medicine* **63**: 2847–2863, DOI: 10.1016/j.socscimed.2006.07.030.

Harman IN, Belcher SE. 2006. The surface energy balance and boundary layer over urban street canyons. *Quarterly Journal of the Royal Meteorological Society* **132**: 2749–2768, DOI: 10.1256/qj.05.185.

Hart MA, Sailor DJ. 2009. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and Applied Climatology* **95**: 397–406, DOI: 10.1007/s00704-008-0017-5.

Holtslag AAM, Van Ulden AP. 1983. A simple scheme for daytime estimates of the surface fluxes from routine weather data. *Journal of*

- Climate and Applied Meteorology* **22**: 517–529, DOI: 10.1175/1520-0450(1983)022<0517:ASSFDE>2.0.CO;2.
- House-Peters L, Chang H. 2011. Modeling the impact of land use and climate change on neighborhood-scale evaporation and nighttime cooling: a surface energy balance approach. *Landscape and Urban Planning* DOI: 10.1016/j.landurbplan.2011.07.005.
- IPCC (Intergovernmental Panel on Climate Change). 2007. In *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, UK, and New York, USA.
- Loridan T, Grimmond CSB, Offerle BD, Young DT, Smith T, Järvi L, Lindberg F. 2011. Local-scale urban meteorological parameterization scheme (LUMPS): longwave radiation parameterization and seasonality-related developments. *Journal of Applied Meteorology and Climatology* **50**: 185–202. DOI: 10.1175/2010JAMC2474.1.
- MacDonald GM. 2010. Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Science* **107**: 21256–21262. DOI: 10.1073/pnas.0909651107.
- Masson V, Grimmond CSB, Oke TR. 2002. Evaluation of the town energy balance (TEB) scheme with direct measurements from dry districts in two cities. *Journal of Applied Meteorology and Climatology* **41**: 1011–1026.
- Myint SW, Giri CP, Wang L, Zhu Z, Gillette S. 2008a. Gillette identifying mangrove species and their surrounding land use and land cover classes using an object oriented approach with a lacunarity spatial measure. *GIScience and Remote Sensing* **45**: 188–208, DOI: 10.2747/1548-1603.45.2.188.
- Myint SW, Yuan M, Cervený RS, Giri P. 2008b. Comparison of remote sensing image processing techniques to identify tornado damage areas from Landsat TM data. *Sensors* **8**: 1128–1156, DOI: 10.3390/s8021128.
- Myint SW, Gober P, Brazel A, Grossman-Clarke S, Weng Q. 2011. Per-pixel versus object-based classification of urban land cover extraction using high spatial resolution imagery. *Remote Sensing of Environment* **115**: 1145–1161, DOI: 10.1016/j.rse.2010.12.017.
- National Solar Radiation Data Base (NSRDB). 2010. [cited November 20 2010]. Available at http://rredc.nrel.gov/solar/old_data/nsrdb/.
- Offerle BD. 2003. *The Energy Balance of an Urban Area: Examining Temporal and Spatial Variability Through Measurements, Remote Sensing and Modeling*, PhD thesis, Indiana University.
- Offerle BD, Grimmond CSB, Oke TR. 2003. Parameterization of net all-wave radiation for urban areas. *Journal of Applied Meteorology* **42**: 1157–1173, DOI: 10.1175/1520-0450(2003)042<1157:PONARF>2.0.CO;2.
- Offerle BD, Grimmond CSB, Fortuniak K, Pawlak W. 2006. Intraurban differences of surface energy fluxes in a central European city. *Journal of Applied Meteorology and Climatology* **45**: 125–136, DOI: 10.1175/JAM2319.1.
- Oke TR, Spronken-Smith RA, Jáuregui E, Grimmond CSB. 1999. The energy balance of central Mexico City during the dry season. *Atmospheric Environment* **33**: 3919–3930, DOI: 10.1016/S1352-2310(99)00134-X.
- Pan Z, Segal M, Arriitt RW, Takle ES. 2004. On the potential change in solar radiation over the US due to increases of atmospheric greenhouse gases. *Renewable Energy* **29**: 1923–1928, DOI: 10.1016/j.renene.2003.11.013.
- Pearlmutter D, Krüger EL, Berliner P. 2009. The role of evaporation in the energy balance of an open-air scaled urban surface. *International Journal of Climatology* **29**: 911–920, DOI: 10.1002/joc.1752.
- Roth M. 2007. Review of urban climate research in (sub)tropical regions. *International Journal of Climatology* **27**: 1859–1873, DOI: 10.1002/joc.1591.
- Salathe EP Jr, Mote PW, Wiley MW. 2007. Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest. *International Journal of Climatology* **27**: 1611–1621, DOI: 10.1002/joc.1540.
- Shashua-Bar L, Pearlmutter D, Erell E. 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning* **92**: 179–186, DOI: 10.1016/j.landurbplan.2009.04.005.
- Shashua-Bar L, Pearlmutter D, Erell E. 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology*. DOI: 10.1002/joc.2177.
- Stone B, Norman JM. 2006. Land use planning and surface heat island formation: a parcel-based radiation flux approach. *Atmospheric Environment* **40**: 3561–3573, DOI: 10.1016/j.atmosenv.2006.01.015.
- Suckling PW, Brazel AJ. 2010. *An assessment of urban-rural differences for incoming solar radiation in central Arizona*. Poster, Topics in Climatology, Annual Meeting Association of American Geographers, April 16, 2010. Available at <http://www.geo.txstate.edu/lovell/Publications/contentParagraph/0111118/document/Suckling-Brazel-Poster.pdf>
- The Arizona Meteorological Network (AZMET). 2010. [cited November 29 2010]. Available at <http://ag.arizona.edu/azmet/>
- U.S. Census Bureau. 2010. *Population Finder*. 2009 [cited November 21 2010]. Available at <http://www.census.gov/>
- Western Regional Climate Center. 2010. *Historical Climate Information* 2010 [cited November 21 2010]. Available at <http://www.wrcc.dri.edu/>
- Wienert U, Kuttler W. 2005. The dependence of the urban heat island intensity on latitude – a statistical approach. *Meteorologische Zeitschriften* **14**: 677–686, DOI: 10.1127/0941-2948/2005/0069.
- Xu W, Wooster MJ, Grimmond CSB. 2008. Modelling of urban sensible heat flux at multiple spatial scales: a demonstration using airborne hyperspectral imagery of Shanghai and a temperature–emissivity separation approach. *Remote Sensing of Environment* **112**: 3493–3510, DOI: 10.1016/j.rse.2008.04.009.