Modeling the urban impact on semi-arid surface climate:

A Case Study in Marrakesh, Morocco

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Prepared for the

Canadian Journal of Remote Sensing

Abstract.

We combine Landsat and MODIS data in the Simple Biosphere Model to assess the impact of urbanization on surface climate in a semiarid city in North Africa.

The model simulates highest temperatures in urban class, with spring average maximum temperature differences to other land cover classes ranging between 1.6 ^{o}C and 6.0^{o}C. During summer, these maximum temperature differences are smallest (0.5^{o}C) with barelands and highest (8.3^{o}C) with irrigated lawns. This excess heating is simulated above and beyond a seasonal temperature average of about 30^{o}C during spring and 44^{o}C during summer. On annual mean, a full urbanization scenario decreases the carbon fixation by 0.13 MtC and increases the daytime mean surface temperature by 1.3°C. This may boost the city energy consumption by 5.72%. Under a 'smart growth' scenario, whereby the city expands on barelands to cover 50% of the study region and all remaining barelands converted to orchards, the carbon fixation is enhanced by 0.04 MtC with a small daytime temperature increase of 0.2^{o}C. Our results indicate that vegetation can mitigate the urban heating.

The hydrological cycle indicates that highest ratio of surface runoff to precipitation (43.8%) occurs in urban areas, versus only 16.7 % for all cover types combined.

Keywords: urbanization, surface climate, Marrakesh, semi-arid

Résumé

On utilise les données Landsat et MODIS dans le modèle simple de la biosphère pour étudier l'impact de l'urbanisation sur le climat de surface d'une ville semi-aride en Afrique du nord.

Le modèle simule les plus hautes températures pour l'urbain. La différence de température maximale moyenne pendant le printemps entre l'urbain et les autres types de couverture de sol varie entre 1.6°C et 6.0°C. Pendant l'été, cette différence est plus faible pour les terres nues (0.5°C) et plus élevés pour les pelouses irriguées (8.3°C). Cet excès de chaleur est simulé en plus et au-dessus d'une moyenne saisonnière de température d'environ 30 °C pendant le printemps et 44 °C en été. En moyenne annuelle, un scénario d'urbanisation complète de la zone d'étude diminue la fixation du carbone de 0.13 MtC et augmente la température diurne moyenne de surface de 1.3 ° C. Ceci peut engendrer une augmentation de la consommation d'énergie de la ville par 5.72%. Dans un scénario de «croissance urbain», dans lequel la ville s'étend sur les terres nues pour couvrir 50% de la région d'étude, et les terrains nus restants sont converties en vergers, la fixation du carbone augmente de 0.04 MtC et la température diurne moyenne augmente seulement de 0.2°C. Nos résultats indiquent que la végétation peut atténuer l'ilot de chaleur urbaine.

Le cycle hydrologique indique que les rapports de l'eau de ruissellement de surface à la précipitation sont plus élevés (43.8%) pour l'urbain, contre seulement 16.7% pour tous les autres types de couvertures de sol combinés.

Mots-clés: l'urbanisation, le climat de surface, Marrakech, semi-arides

1. Introduction

To date, 54% of the world's population lives in urban areas and this proportion is expected to increase to 66% by 2050 (UN, 2014). In the developing world, particularly Africa and Asia, cities are expected to host nearly 90% of the projected population growth (UN, 2014). Certainly, urbanization is a sign of human development and thriving economic, social and political life; however in ecological terms, it is the most significant and long lasting form of anthropogenic land transformation. In cites, large fractions of natural land cover, including vegetation, are replaced by mostly dark and impervious surfaces. This transformation reduces photosynthesis and evaporation, and alters water infiltration and surface runoff. Furthermore, the dark surfaces absorb most of the solar energy and contribute to warm the cities compared to their rural surrounding, and form what is known as the Urban Heat Island (UHI). Urban buildup also affects the roughness of the surface elements and as such modifies the turbulent exchanges of momentum, energy and water fluxes at the land-atmosphere interface. Through these mechanisms, urbanization affects surface climate indicators such as temperature, precipitation, humidity, and near-surface wind (Oke, 1997; Arnfield, 2003; Masson, 2006; Shepherd, 2006; Bounoua et al., 2009).

The most documented effect of urban climate modification is the so-called UHI effect, characterized by urban areas warmer than their rural, generally more vegetated, surroundings. Previous studies showed that this warming, attributable to land cover change, is in the range of less than 1°C to over 8°C in cities around the world (Oke, 1987; Kłysik et al., 1999; Rizwan et al., 2008) and is a function of urban morphology and physical characteristics, urban extent, waste heat release, and regional climate factors (Arnfield, 2003; Imhoff et al., 2010; Zhang et al., 2010). Most of the previous urban climate studies have primarily focused on industrialized cities located in mid-latitude temperate climate zones and only few have been performed in medium size cities of developing countries, such as in semi-arid Africa where much of the future urban growth is projected to take place and where the population is more vulnerable to climate impacts (UN 2014; Field 2014). A recent study showed that UHI effects are not strongly marked in a Mediterranean city where buildings are light colored and thus more reflective than surrounding vegetated lands, however the study showed the city still warmer than surroundings during summer daytime and slightly cooler in winter (Bounoua et al., 2009).

In this paper, we assess the impact of urbanization, as a form of land use, on the surface climate of Marrakesh, a semi-arid continental city in central Morocco. Marrakesh, also known as the 'Red City' in reference to its rose-tinted buildings, has experienced a significant urban growth during the last couple of decades. We use the Simple Biosphere model (SiB2) of Sellers et al., (1996.a) as modified by Bounoua et al., (2009) to examine the impact of the impervious surface area (ISA) on the surface carbon, energy and water exchanges at the land-atmosphere interface at daily, monthly and seasonal time-scales. We also analyze the UHI across the city landscape and estimate the contribution of vegetation in reducing the UHI and local energy use.

2. Study area

Marrakesh is the fourth largest urban center in Morocco, a northwestern African country (Figure 1). Its population exceeds 1 million persons, 79% of which live within the conurbations of the city core. The city has undergone a significant urban growth and the built area has expanded from 2000 ha in 1970 to 4500 ha in 1990 and reached 15 000 ha in 2010 (ONEM 2011).

Marrakesh is characterized by a semi-arid continental climate, with mild damp winters and hot dry summers. Its mean annual temperature is around 20°C with monthly mean temperatures varying between 12.5^{o}C in winter (January) and 29^{o}C in summer (August) and summer maxima reaching peaks around 40 ^{o}C. Precipitation falls between November and April and reaches a climatological mean annual total fluctuating between 150 and 350 mm.yr^{1}. Outside the rainy season, the atmosphere remains dry with a high evaporative demand (Duchemin et al. 2006, Chehbouni et al. 2008).

Green spaces that once occupied two-thirds of Marrakesh, recognized in the past as "the city of a thousand gardens” have now dwindled as a result of urbanization. Most of the remaining green landscape is located in peripheral areas, and only few gardens survived within the dense old city. Qualitatively, these green spaces are dominated by local species such as grass, sour orange, olive and palm trees, and are maintained by resource augmentation such as fertilization and irrigation. The city is surrounded by natural sparse short vegetation during the rainy season, turning to bare ground as a response to moisture scarcity during summer. The western part of the city is still dominated by irrigated farming.

3. Data and Model

We developed a land cover map to differentiate between the impervious surfaces (built up) and other vegetation types using Landsat TM-5 images at 30m spatial resolution. The time varying biophysical parameters characterizing the vegetation were obtained using the land cover map and time series of the Normalized Difference Vegetation Index (NDVI) derived from the Moderate resolution Imaging Spectroradiometer (MODIS) at 250 m spatial resolution. Using the derived land cover and the biophysical parameters, we ran the Simple Biosphere Model SiB2 (Sellers et al., 1996.a) at 250mx250m forced by local climate variables to predict the canopy, ground and soil water content, and the carbon, energy and water vapor fluxes that are exchanged between the land-vegetation and the canopy air space.

3.1 Land cover:

The land use in the city of Marrakesh and its surrounding areas is grouped into most representative land cover classes. Each of these classes has been mapped to one of the SiB2 classes (Sellers et al., 1996.a). In addition to the impervious surface (IS) that represents the urban class; four other land cover classes were defined. The orchards with local evergreen trees (olive, palm and sour orange trees) were assigned SiB2 class 06; cereal and other irrigated crops were assigned SiB2 class 12; irrigated grassland, present mainly in golf courses, was assigned class 07; and the bare land with sparse vegetation was assigned SiB2 class 09.

To map the land cover (LC) over the study region, we used supervised maximum-likelihood classifications of multitemporal Landsat Thematic Mapper (TM-5) data. We combined 4 cloud free images (February 2010; June 2010; November 2010; January 2011) covering different seasons in 2010 to resolve the confusion between IS and bare soil during summer, and used phenological variation to distinguish between different vegetation types. Landsat images were calibrated, projected to latitude-longitude and resampled to 25m. Two separate sets of training samples, representative of all vegetation types present in the study area were obtained from field observations; the first set was used in the maximum likelihood classifier to produce the land cover map and the second set was used to validate it. The resulting map shows 94% overall accuracy (Figure 2).

The Landsat derived land cover map at 25m was then aggregated to a 250mx250m grid for climate modeling purpose. Each 250mx250m Climate Modeling Grid (CMG) contains aggregated fractions of land cover types from the original Landsat-based high resolution map at 25m (Figure 3). This methodology is practical for modeling, as it scales up the land cover to the CMG forcing at 250x250m but retains the heterogeneities of the landscape in the form of fractions of land cover types co-existing in the CMG.

3.2 Biophysical data

A 16-day composite time series of MODIS NDVI at 250mx250m spatial resolution (MOD13Q1) spanning the period January to December 2010 was generated for the study region. For that, data were extracted from one MODIS tile (h17v05), co-registered to the same spatial reference as the 250mx250m land cover map and filtered using pixel-level quality-assurance information to generate high quality vegetation index values.

It is known that at 250mx250m horizontal pixel size, the MODIS NDVI value is the spectral response resulting from the contribution of all land cover classes co-existing in the pixel, and is therefore a value representing an average over the pixel, that ranges between the highest NDVI value describing the greenest land cover type and a low NDVI value describing the darkest land cover type within that pixel.

To resolve sub-pixel heterogeneity of NDVI, we used high resolution maximum NDVI obtained from Landsat during the peak of the growing season over the region. We computed the Landsat-based domain average maximum NDVI for each land cover class $NDVI_L$ and ratios were obtained, for each class, by dividing $NDVI_L$ by the maximum 250mx250m NDVI value from MODIS. These ratios were then used to scale up the MODIS NDVI for each LC class. Figure 4 shows the domain average seasonal variation of the MODIS scaled NDVI for each LC class existing in the study region. This NDVI scaling technique yielded results comparable to those obtained using a Kalman filtering method, though with slightly higher maxima (Sedano et al., 2014).

This scaled NDVI and land cover map at 250m spatial reolution, were then used to compute biophysical parameters describing the physiological, morphological and optical characteristics of the land cover, such as the fraction of the photosynthetically active radiation (FPAR), the leaf area index (LAI), the greenness fraction of the canopy, the roughness length and the zero plan displacement at 16-day intervals for each land cover type existing in the 250mx250m. The computational procedure follows the original algorithms developed in Sellers et al. (1996-b) and modified by Bounoua et al. (2015.a).

3.3 Model description

For this study, we use the Simple Biosphere Model of Sellers et al. (1996.a) as modified by Bounoua et al. (2009) to assess the impact of urbanization as a form of land use on surface climate in Marrakesh. SiB2 is a biophysically based land surface model that computes the exchanges of energy, water, carbon and momentum explicitly accounting for 12 land cover classes, including an urban class, entirely characterized by satellite data.

The model is fed with satellite-based biophysical parameters describing the seasonal variation of the vegetation phenology as well as time independent, vegetation type–dependent parameters characterizing the physiological, optical and morphological properties of the vegetation (Sellers et al., 1996.b).

SiB2 predicts 9 prognostic state variables: three temperatures describing the canopy, the ground surface, and the deep soil, respectively; two water stores, representing the interception of liquid and solid water by the canopy and the ground; three soil moisture stores with different depths, and a canopy stomatal conductance (Sellers et al., 1996.a). The model is driven by short- and long-wave radiation, convective and large scale precipitation, specific humidity, surface air temperature, surface pressure and wind speed at some reference height above the canopy and returns components of the latent heat flux consisting of the canopy and ground interception loss (potential evaporation from canopy and ground surfaces), the soil evaporation, and the canopy transpiration. It also returns the soil and canopy sensible heat fluxes, the reflected and emitted radiation fluxes, and the net photosynthetic carbon flux along with other components of the surface energy and water budgets.

SiB2 uses the two-stream approximation to compute snow free surface albedo from soil and canopy reflectance. Leaf reflectance and transmittance for near infrared and visible wavelengths for both green and dead leaves is prescribed for each of the 12 SiB2 LC classes. Soil reflectance is obtained from the Earth Radiation Budget Experiment- ERBE (Harrison et al., 1990).

SiB2 estimates photosynthesis using a coupled photosynthesis-conductance module to simulate the simultaneous exchange of carbon intake and water vapor diffusion in and out of the leaf, respectively. Carbon assimilation is calculated from FPAR constrained by light limitation, environmental conditions, and a prescribed vegetation dependent maximum photosynthetic capacity (Vmax). From the canopy net assimilation rate (Ac), the canopy stomatal conductance (g_c) is calculated as:

$$g_c = m\frac{A_C}{C_S}h_S p + bL_T \tag{1}$$

Where p is the atmospheric pressure and L_T is total LAI; m is the stomatal slope factor and b the minimum stomatal conductance discriminating between C3 and C4 photosynthesis. While the control of stomatal conductance by atmospheric humidity is explicit through h_S, effects of temperature and soil moisture stresses are implicit in Ac (Bounoua et al., 2004); Cs is the intercellular CO_2 concentration.

The convective and large scale precipitations in SiB2 are treated differently and are distributed into canopy interception and throughfall. The canopy interception is evaporated back to the atmosphere at potential rate or contributes to throughfall if it exceeds the canopy holding capacity. The throughfall and water dripping from the canopy is added to the ground liquid water store. At this level, water can evaporate or infiltrate into a shallow surface layer if the ground storage capacity is exceeded. If the infiltration rate exceeds the infiltration capacity of the soil, the excess water contributes to surface runoff. Similarly, water from the surface layer can either evaporate or infiltrate into the root zone layer from which it can flow up into the surface layer, infiltrate into the deep layer, be used by plants for transpiration or contribute to runoff. The deep soil water can diffuse up and contributes to total runoff via gravitational drainage.

3.4 Climate and Soil Data

The climate data used in this study are obtained from the Modern Era Retrospective Analysis for Research and Applications (MERRA) of the Goddard Earth Observing System data assimilation system (GEOS-5) at 0.25 x 0.25 degrees spatial resolution (Rienecker et al., 2011). We extracted hourly data for the year 2001 and then bias-corrected them using hourly observations from 3 meteorological stations located in the study area (LMI-TREMA, 2010). The study area is relatively small and because of proximity, the meteorological stations did not exhibit sensible difference between the recorded surface temperatures and the precipitations. We therefore apply the same climate forcing to the entire study area.

According to the FAO-UNESCO Soil Map of the World (FAO, 2007), the soil texture in our study area is loam with no important spatial variations. The soil is then assigned the properties of SiB2 soil type 03 characterizing loamy soils (Sellers et al., 1996.b).

The topography was obtained using the global digital elevation model (Farr et al., 2000) resampled to 250m over the study area.

4 Model simulations

The land cover maps and their associated biophysical fields are used as surface boundary conditions to SiB2. The same atmospheric forcing and soil data are used in all simulations so that the model responses are exclusively attributable to land cover and its associated phenology.

Each land cover type was affected the morphological, optical and physiological parameters described in Sellers et al. (1996.b). The built up, also referred to as 'urban' class in this study, is labeled class 8, and is assigned SiB2 class 9 (shrubs with bare soil) parameters with modifications as in Bounoua et al. (2009 and 2015.b):

- A lower soil reflectance obtained as the average reflectance of typical impervious surfaces (such as parking lots, bricks and pavement) existing in the study area (Roberts, D. A. and M. Herold 2004)
- The heat absorption function is represented by an average heat capacity of a thin concrete slab augmented by the heat capacity of water and snow when they exist on the ground.
- An augmented surface roughness.
- A top soil layer completely impermeable to water having 2 mm maximum holding capacity.

Over the study region, the peak vegetation growth corresponding to the rainy season occurs in March. During the study period (2010), three vegetation types (06, 07 and 12) exhibited a relatively high NDVI during the summer time, outside of the local rainy season. Since the last significant precipitation event was recorded in March and high LAI cannot be sustained without sufficient water, we infer that these vegetation types were irrigated. This biophysical configuration and inference of irrigation is consistent with field studies over the same region and time period (Ezzahar et al., 2009; Rabi et al., 2009). An advanced irrigation technique (Bounoua, 2010) was then applied to these three land cover types to sustain observed LAI in the absence of precipitations. The irrigation scheme provided results comparable to observations for the region (Figure 5).

Five simulations were integrated, one for each land cover type, at 250mx250m spatial resolution and hourly time-step. This way model outputs describe the individual responses of each cover type to the same atmospheric forcing, but overall grid cell outputs are obtained as the average response of all cover types co-exiting in this grid weighted by their respective fractions. The simulations were span-up for 3 years starting from initial conditions based on climatology and soil moisture initialization following (Stefanova, 2001) and then integrated forward 3 years. The analysis presented here is based on outputs from the last annual cycle.

5. Results and discussion

In the following sections we analyze SiB2 simulated hourly outputs for an a priori randomly selected grid cell having a mix of all land cover types present in the study area (Table 1) as well as seasonal results averaged over the study area (Figure 1) during the growing season: February, March, April (FMA) and outside of the growing season: June, July, August (JJA).

5.1 Hourly response: the case of cropland

Figure 6 shows the model hourly response of cropland in the selected grid cell (Table 1). As expected, vegetation physiology responds to both LAI and climate forcing. A relatively high photosynthetic activity is simulated during the growing season (FMA) when high LAI values are observed. Although precipitation was present during this season, some additional irrigation was required to sustain the observed LAI. In SiB2, irrigation is based on the assumption that, in its natural state, vegetation Leaf Area Index is in quasi-equilibrium with its local climate, soil and nutrient resources (Bounoua et al., 2010). Irrigated lands in semi-arid regions are not in equilibrium with local climate, and this is expressed by high observed LAI and lack of sufficient rainfall. When this happens in the model, it translates to vegetation being water-stressed and the modeled photosynthesis suppressed. Bounoua et al. (2010) postulated that the degree to which the satellite observed LAI of irrigated lands vary from what would be expected under equilibrium conditions is related to the amount of irrigation water used. Given the land cover type and its physiological attributes, water is added to the crop to reduce its water stress to a crop-type dependent level. In SiB2, the water stress function depends on the water content in the root zone, itself a function of the precipitation amount, soil hydraulic properties and the amount of LAI. A stress value of 1 corresponds to no-stress while 0 represents maximum stress. When the soil water content in the root zone reaches a low threshold, the water stress function inhibits plant's photosynthesis, indicating disequilibrium between the satellite observed LAI and the amount of water in the root zone, and triggers the irrigation mechanism. There is no simultaneous irrigation when rainfall is present.

It is worth noting that the model does not leak, almost all the rainfall and the additional irrigation is used by vegetation or lost to evaporation, only a small fraction of the incoming water is expelled as overland flow when the precipitation rate exceeded the infiltration capacity of the soil. Soil moisture is a direct response to precipitation and soil properties, the surface layer has a shallow depth of 2 cm (except for urban where it is 2mm) and thus responds almost instantaneously to precipitation and irrigation. In this CMG, surface layer soil moisture is maintained at about 0.12% in the absence of incoming water. On the other hand, the root zone water store responded to the precipitation anomalies with a time lag, dampening thus the precipitation anomalies as they go down through the hydrological system. After the harvest, in mid-April, the water store in this soil layer has decreased slowly over 4 months because of lack of precipitation and irrigation and a low LAI.

5.2 Seasonal Response

5.2.1 Carbon budget

In SiB2, the carbon assimilation response is strongly dependent on $V_{max,}$ a vegetation-dependent maximum photosynthetic capacity (Sellers et al., 1996.b). Each land cover, forced by the same climate, produces different responses (Figure 7). During the growing season (FMA), the carbon assimilation rate (net photosynthesis) of the evergreen trees (T06) and grassland (T07) reached maximum values of 15.98 and 13.50 $\mu mol.m^{-2}.s^{-1}$, respectively whereas, cropland (T12) has assimilated carbon at a lower rate, about 7.04 $\mu mol.m^{-2}.s^{-1}$ (Table 2, Figure 7.a). This is mainly due to the high observed LAI for vegetation type 06 and 07 compared to type 12, and also to the fact that cropland is a C3-plant (Sellers et al., 1996.b) and is less water efficient; it assimilates about half as much carbon as C4 (T06 and T07) plants for the same amount of water use. It is also less resistant to high temperatures than its C4 counterparts. Indeed, the canopy conductance for cropland reaches its maximum around 09 AM local time, and is then slightly reduced during the course of the day, when high temperature stress reduces the carbon assimilation rate. In fact, the model parameters affected to cropland indicate that this LC class is less adapted to the region’s climatology and is sensitive even to the growing season maximum temperatures. For example, during the growing season, The average maximum surface temperature ranges between 30°C in March and 40°C in April, whereas the half inhibition physiological limit for the crops canopy temperature in the region is 35°C (Sellers et al., 1996.b).

Bare and urban lands, type 09 and 08, respectively include some sparse vegetation mixture during the growing season which contributes little in carbon uptake; less than 0.44

μmol.m^{-2}.s^{-1} for the bare land and less than 0.012 μmol.m^{2}.s^{1} for the urban during the entire year.

Outside of the growing season, photosynthetic activity persists only for the evergreen orchards and grasslands (type 06 and 07) which are maintained by irrigation. The assimilation rate of other land cover types is limited by high temperature and lack of water (Table 2, Figure7.b).

Over the entire study area, vegetation has assimilated 0.13 MtC [1 MtC = 10^6 Tons of Carbon] during the year 2010, 46 % of which occurred during the growing season. Croplands which occupy 27.79 % of the area contributed 41.44 %, followed by the orchards which cover only 8.8 % of the study area yet contributed 36.33 % of the total carbon sequestration. With 4.75% areal coverage, grasses (type 07) assimilated 15.26 % of the total carbon uptake. On the other hand, Urbanized and bare lands which represent 58.66% of the area has contributed a small amount, 6.97% of the total sequestration (Table 3). This suggests that, provided water is not limiting, the city of Marrakesh could increase significantly it yearly carbon sequestration amount if the bare lands are used to grow evergreen trees, and the urban areas include more green spaces and trees.

5.2.2 Hydrological budget

The water balance, for the selected grid cell (Table 1), averaged during the growing season (FMA) and outside the growing season (JJA) is illustrated in Figure 8. The model indicates that the total 109 mm of rainfall received during the growing season were not enough to sustain the observed LAI for some land cover types and irrigation was thus required (see section 4). The model irrigation scheme delivered an additional 145 mm for the evergreen trees, 150mm for crops and 226 mm for grasslands. The total incoming water was mainly partitioned between two components: 1) evapotranspiration which includes the canopy and ground transpiration and interception, and 2) the total runoff which accounts for surface and gravitational runoff. A small fraction of the remaining water goes into replenishing the canopy and ground water storage (dwg). In the case of crops, 77 % of the total incoming water was lost to evapotranspiration, 15% was expelled as total runoff, and only 8% was used to replenish the depleted canopy and ground water stores.

Outside the growing season (JJA), the total precipitation accumulation was 27mm. During the same period, grasslands representing golf courses in the study region consumed an additional 380 mm of irrigation water. Of the total incoming water 392 mm was lost to evapotranspiration (96.3%) and only 3.7% was discharged as runoff. This suggests that grasslands are the most water-consuming vegetation type over the region and while they have an important economic value as a tourist attraction, they require about 15 times more water than what the region receives during summer.

To assess the land cover water discharge response to the same water inputs, we carried out additional model simulations with excluded irrigation. The results, averaged over the study area, show that highest total surface runoff was recorded in urban areas, where it represents 43.8 % of incoming rainfall versus only 16.74 % for all other land cover types combined (Table 4).

5.2.3 Surface energy budget

To better isolate the urban effect on land surface climate, we compare it to its non-urban surrounding and address the urban/non-urban surface energy balance differences. We limit the discussion to the growing season when vegetation is active and has an impact on the energy balance. In SiB2, the flux of net energy absorbed by the canopy/ground is distributed into canopy/ground heat storage, canopy/ground sensible heat, canopy/ground transpiration and interception, and canopy/ground heat loss to snow melt.

The different components of the surface energy balance for daytime and nighttime and for the growing season are illustrated in Figure 9. During daytime, the built up absorbs the highest amount of incoming energy, about 200 W.m-^{2}, because of a lower surface reflectance compared to other land cover types. 98 % of this energy is absorbed by the ground since no or little vegetation is present in the urban area. Out of the total absorbed energy, a small fraction 13.6 % goes to ground evaporation and 19.2% is stored in the soil. The largest fraction 67% goes into sensible heat. At night, the energy fluxes are reversed. The soil restores energy mostly through sensible heating with amplitude much less than during daytime (Figure 9.b). The energy distribution for the bare land (T09) resembles closely the urban type, except for larger canopy transpiration due to the presence of some sparse vegetation in the bare land during the growing season.

The different vegetation types exhibit similar distributions of absorbed energy. However, the evergreen orchards (type 06) have the highest LAI and thus the highest canopy absorbed energy of 66 W/m^{2} or 41 % of total absorbed.

A large part of the absorbed energy is dissipated by sensible and latent heat fluxes to the air. Canopy latent heat flux is controlled by vegetation density, vegetation type and in these simulations by irrigation. For example, because of high LAI, the orchards of evergreen trees dissipate 91 W.m^{-2} as latent heat flux (total evapotranspiration of the canopy and the ground) during daytime versus only 27.7 W.m^{-2} for bare land with lower LAI. Furthermore and as expected, the most irrigated vegetation produces the highest latent heat flux. For example for the grassland, the average daytime mean latent heat flux is 103.4 W/m^{2} versus 91 W/m^{2} for the evergreen trees. Land cover types with lower leaf area such as urban and bare lands dissipate most energy in form of sensible heat.

This form of heat redistribution between the ground/canopy and the canopy air space is governed by the level of surface turbulence, itself dependent on the aerodynamic properties of the canopy. A surface covered by short vegetation (grassland and bare land) dissipates more energy to the canopy air space during daytime compared to taller vegetation (evergreen trees), but the opposite happens to hold true during the nighttime because of relatively stable air and low turbulence activity (Oke, 1982). The remainder of the absorbed energy is stored in the canopy and ground and contributes to increase their temperatures during the day.

The model simulates the warmest temperature for the urban class, followed by bare land and then by the other land cover types (Figure 10). Averaged over the growing season and the study region, the surface temperature differences between urban and other land cover types range between 1.6°C and 6.0°C at 1PM local time and between 0.7°C and 1.1°C at 5 Am (table 5).

The thermal contrast between urban and vegetated covers is more pronounced during summer daytime (up to 8.3 °C) when the air temperature and the evapotranspiration from irrigated vegetation are high.

Land cover fraction-weighted average daytime and nighttime surface temperatures are obtained during and outside the growing season (Figure 11). The highest surface temperatures are simulated in the center of the study region where the highest built up density is located.

Further analysis indicates that the ISA fraction explains about 73% of the temperature variance in the study region during the growing season daytime and about 98% during nighttime (Figure 12). The stronger relationship during nighttime is due to lack of transpiration from non-active vegetation (see Figure 9.b). Indeed, when the ISA fraction is less than 100%, the remainder of the grid is occupied by transpiring vegetation, in most cases irrigated, creating thus cooler surface temperatures. A similar daytime/nighttime relationship is observed outside of the growing season.

The surface temperature differential between the urban core with high ISA and its peripheral zones creates the so-called urban heat island (UHI). We represent the UHI using surface temperature profiles across the city with ISA intervals of 20% (Figure 13) for: 1) a fully urban scenario (100% ISA), 2) a weighted average scenario representing the actual condition and comprising all classes (including the urban class) weighted by their fractions, and 3) a fully vegetated scenario in which ISA is replaced by a weighted mix of vegetation only (e.g., Bounoua et al., 2015.b). The fully vegetated scenario is a representation of a pre-urban condition, and the departure of its temperature from the actual condition represents the cumulative impact of urbanization on the city's temperature. Using this comparison, we find that during the growing season, urbanization has increased the urban center surface temperature by 1.9°C during daytime and 0.7°C during nighttime. Furthermore if the city, within its actual limits were to become fully urbanized, the temperature could rise by up to 2.1°C at the edges of the city during the day and 0.8°C at night without changes in the city core which is already fully urban. During summer time, in the absence of precipitation and irrigation, the surface temperature of surrounding rural areas becomes warmer and reduces the difference with the urban core to 1.5°C (Figure 13).

5.3 Future urban growth

Four scenarios are simulated to estimate the impact of future urban growth on the Marrakesh surface climate, the first one (PU) simulates the pre-urban situation where the urban fraction in each grid cell is replaced by vegetated land cover types co-existing in the grid in the same proportion as in 2010. The second scenario represents the business as usual scenario and assumes an extension of the built up to cover 50% of the study region at the expense of all vegetation types and proportionally to their fractions in 2010 (BAU50). The third scenario, labeled smart growth scenario (SMG50) also assumes an extension of the built up to cover 50% of the study region, but allows the urban expansion to occur first in bare lands, with all remaining bare lands converted to evergreen orchards. The last scenario, U100 describes the most extreme situation where the built up covers 100% of the study region. The land cover composition of each scenario is shown in (Table 6).

A comparison of the pre-urban scenario to the 2010 conditions, considered as control, shows that the built up has significant effects on the surface temperature, surface runoff and carbon sequestration. Over the study region, the built up has added an additional 0.3°C to daytime and 0.1°C to the yearly mean nighttime temperature compared to PU. It has also increased the ratio of surface runoff to precipitation by 4.56%, and decreased the yearly total carbon uptake by 0.026 MtC (Table 7).

Future projection scenarios show that the increase of the built up area will exacerbate the impact of urbanization on surface climate. The simulation of the second scenario BAU50 shows that an urban growth to 50% of the study region area following a business as usual scenario will increase day and night temperatures by 0.5°C and 0.2°C, respectively, decrease the yearly total carbon sequestration by 0.05 MtC, and increase the ratio of surface runoff to precipitation by 8.95% compared to the actual conditions. However, the same urban expansion under a smart growth scenario (SMG50) seems to alleviate the impacts on daytime mean surface temperature which is projected to warm up only 0.2°C, and boost the carbon sequestration by 0.04 MtC; this ‘selective’ urban growth along with evergreen trees plantations in bare lands would counterbalance 60% of the daytime temperature increase by urban expansion and would sequester 31% more carbon compared to actual situation (Table 7 and Table 3). The extreme case scenario U100, will reduce all the carbon sequestration (0.13 MtC) of the study area, increase the 2010 mean surface temperature by 1.3°C during the day and 0.7°C during the night, and will significantly increase the ratio of surface runoff to Precipitation by 22.47%.

The surface temperature in the city of Marrakesh has a direct impact on the energy use. Temporal analysis of monthly total energy consumption in the city of Marrakesh (RADEEMA, 2014) and corresponding mean air temperature during the year 2013 and 2014 shows that mean air temperatures that are higher than 20 °C or lower than 13 °C induce an increase in energy use to meet the needs of cooling/heating (figure 14). An increase of 1°C in the maximum mean air temperature recorded in the period 2013-2014 (31 °C) will cause an increase in energy use of 4.4%, and a decrease of 1 °C in the minimum mean air temperature recorded in the same period (12 °C) will cause an increase in energy use of 2.2%. Our analysis shows urban expansion can potentially add a daytime warming between 0.2°C for the smart growth scenario and 1.3 °C for the fully urban. This could correspond to an increase in energy use between about 1% and 5.72%. While existing cities cannot be reengineered, their future development can be planned to minimally impact their environment.

6. Conclusing Remarks

The city of Marrakesh is small in size compared to megacities around the world or even compared to other cities in Morocco such as Casablanca and Tanger. However, with a population of about 1 Million, it is in full economic expansion and is an important tourist destination, and as such it is poised to grow faster in the future. By 2010, Marrakesh areal extent has increased by more than 7 folds compared to 2000 (ONEM 2011) and its actual urbanization rate is projected to be higher than the national average (HCP 2004). Most of urbanization in Marrakesh has occurred in fertile irrigated agricultural lands in proximity of water sources and its expansion may be a challenge considering limited or decreasing water availability.

Satellite data analysis shows the study region still has its largest area occupied by agriculture (36.59%), second only to bare lands which represent 41.78%. Other irrigated grasslands occupy a small fraction of 4.75%. Within this land cover mix, urbanization appears as a relatively small fraction (16.88%), yet its impact on carbon fixation, surface temperature and water discharge is significant.

Over the study region, agricultural lands fixed 77.77% of the total annual carbon uptake of 0.13 MtC and the irrigated grasslands fixed 15.26 % for a total 93.03%. Conversely, urban and bare lands, which represent 58.66% of the area, have contributed only 6.97% of the total carbon uptake. This implies that, if water is not limiting factor in the future, the city of Marrakesh has enough space to significantly increase its carbon sequestration and reduce its carbon footprint.

The hydrological analysis averaged over the study region, indicates that highest ratio of surface runoff to precipitation occurs in urban areas, where 43.8 % of incoming rainfall is expelled as surface runoff versus only 16.74 % for all other land cover types combined. This suggests that a mix of vegetation in an urban setting can significantly influence the water discharge, and the ratio of surface runoff to precipitation can be used as an indicator for projecting the distribution of surface runoff given a rainfall prediction event (see also Bounoua et al., 2015.b).

Averaged over the study region during the growing season, we find the difference in maximum surface temperature, between the urban and other land cover types to vary between 1.6°C and 6.0°C, whereas the difference in minimum temperature ranges between 0.7°C and 1.1°C. This simulated thermal contrast is even more pronounced during summer daytime where a temperature difference between the urban and irrigated lawns and golf courses could reach up 8.3 °C. Our analysis shows the daytime and nighttime mean surface temperatures to be strongly correlated to the ISA fraction. However lower daytime surface temperatures are simulated for small ISA fractions suggesting an important role of vegetation evaporative cooling on the determination of surface temperature. In a scenario where the city, within its actual limits, were to become fully urbanized, we find the surface temperature to rise by 2.1°C at the edges of the city during the day and 0.8°C at night during the growing season, without changes in the city core. On annual mean and over the study region, however, the daytime mean surface temperature could increase by 1.3°C which may lead to an increase in energy consumption of about 5.72%.

We find the mix and amount of vegetation in an urban area to be an important modulator of surface temperature and can be used as a natural mitigation mechanism to reduce the excess urban heating.

Acknowledgement

During her stay at NASA Goddard Space Flight Center, Asia Lachir was fully funded by Fulbright Joint Supervision Program.

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Table 1: Land cover types and fractions in the selected climate modeling grid located at (longitude= 8.031° W, latitude =31.68° N). T06: Orchards with evergreen trees, T07: Grassland, T08: Urban, T09: Bare land, T12: Cropland.

land cover type	**T06**	**T07**	**T09**	**T12**	**T08**	**TOTAL**
Fraction in the CMG (%)	14	5	24	12	45	100

Table 2: Daily statistics of the Fraction of Photosynthetically Active Radiation (FPAR), assimilation rate (As) (µmol.m^{-2}.s^{-1}) and stomatal conductance (Cs) (m. s^{-1}), for all land cover types and for the weighted average, during the growing season (FMA) and outside of the growing season (JJA).

land cover type		**T06: evergreen trees**		**T07: grassland**		**T09:bareland**		**T12: cropland**		**T08:urban**		**Weighted average**	
February March April	**Mean FPAR**	0.85		0.68		0.06		0.51		0.00		0.22	
		As	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**
	minimum	-0.12	1.37	-0.11	0.67	-0.02	0.05	-0.31	0.14	-0.001	0.004	-0.07	0.26
	maximum	15.98	2.43	13.50	1.63	0.44	0.14	7.04	1.52	0.012	0.007	3.85	0.57
	mean	4.42	1.70	3.75	0.97	0.17	0.08	2.58	0.61	0.004	0.005	1.16	0.38
June July August	**Mean FPAR**	0.23		0.21		0.05		0.08		0.005		0.07	
		As	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**	**As**	**Cs**
	minimum	-0.07	0.19	-0.07	0.19	-0.04	0.03	-0.10	0.02	-0.001	0.002	-0.03	0.04
	Maximum	7.12	0.60	5.84	0.68	0.39	0.13	1.02	0.25	0.008	0.004	1.39	0.16
	mean	2.60	0.35	2.11	0.38	0.08	0.04	0.24	0.06	0.001	0.003	0.52	0.09

Table 3: Carbon assimilation rate per land cover type aggregated over the study region in g.m^{-2}, and total carbon uptake in (MtC) during the growing season (FMA), outside of the growing season (JJA) and the yearly total. The ratio (type Vs domain) represents the carbon uptake of a specific land cover type as a percent of the fraction-weighted total carbon uptake of all land cover types co-existing in the domain.

Land cover type	**T06**	**T07**	**T08**	**T09**	**T12**	**Weighted Average**
fraction	8.8	4.75	16.88	41.78	27.79	100
FMA (g/m2)	388.06	306.09	0.35	13.95	194.43	108.60
FMA (MtC)	0.017	0.007	0.00003	0.003	0.027	0.055
Ratio (Type Vs Domain)	31.45	13.39	0.05	5.37	49.74	100.00
JJA (g/m2)	273.50	215.81	0.10	6.12	22.92	43.27
JJA (MtC)	0.012	0.005	0.00001	0.0013	0.0032	0.022
Ratio (Type Vs Domain)	55.63	23.70	0.04	5.91	14.72	100.00
Yearly total (g/m2)	1030.88	802.27	0.88	41.28	372.43	249.71
Yearly total (MtC)	0.046	0.019	0.0001	0.009	0.053	0.13
Ratio (Type Vs Domain)	36.33	15.26	0.06	6.91	41.44	100.00

Table 4: Annual surface runoff response averaged over the study region, the weighted average represents a weighted average for all land cover types including the urban type and the vegetation weighted average represents the weighted average for all vegetation classes excluding urban. All land cover types received the same amount of total precipitation of 277.3 mm.

Type de vegetation	T06	T07	T08	T09	T012	Weighted Average.	Vegetation Weighted Average
Vegetation fraction %	8.80	4.75	16.88	41.78	27.79	100.00	83.12
Total surface runoff (mm)	36.43	45.95	121.41	50.55	43.51	59.09	46.43
Ratio surface runoff/Precipitation (%)	13.14	16.57	43.78	18.23	15.69	21.31	16.74
Contribution to total surface runoff in study region (%)	5.4	3.7	34.7	35.7	20.5	100	65.3

Table 5: Minimum and maximum surface temperature differences between urban and other land cover types in (°C) over the study region during the growing season (FMA) and outside of the growing season (JJA).

	L C	**T06**	**T07**	**T09**	**T12**
FMA	Min ΔT (°C)	1.0	1.1	0.7	0.7
	Max ΔT (°C)	5.7	6.0	1.6	4.7
JJA	Min ΔT (°C)	0.8	1.6	0.9	0.8
	Max ΔT (°C)	4.4	8.3	0.5	1.8

Table 6: Projection Scenarios: fractions of each land cover type in the study region for different scenarios (see text for details).

Fractions	Control	PU	BAU50	SMG50	U100
T 06	8.8	10.59	5.29	17.47	0
T07	4.75	5.71	2.86	4.75	0
T08	16.88	0	50	50	100
T09	41.79	50.28	25.14	0	0
T12	27.78	33.42	16.71	27.78	0
total	100	100	100	100	100

Table 7: Future projections of the annual mean weighted average surface temperature and yearly total surface runoff and carbon sequestration, over the study region. We present the differences of each scenario from the control.

Scenarios	PU	BAU50	SMG50	U100
Carbon sequestration (MtC)	0.026	-0.05	0.04	-0.13
Night mean surface temperature	-0.1	0.2	0.3	0.7
Day mean surface temperature	-0.3	0.5	0.2	1.3
Total surface runoff (mm)	-12.65	24.83	22.25	62.31
Ratio of surface runoff to precipitation (%)	-4.56	8.95	8.02	22.47

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Figure 1 : a) Localization of study area, upper left corner (longitude=-8.14°; latitude=31.72°), lower right corner (longitude = -7.88°; latitude = 31.53°); b) Different Types of urban settings in Marrakesh

Figure 2: Landsat-based Land cover over the study area at 25m spatial resolution

Figure 3: Fraction of a Land cover type in 250m grids.

Figure 4: Domain average scaled NDVI time series for each land cover type at 250m spatial resolution during 2010 (see text for details).

Figure 5: Rainfall events (blue) and irrigation in mm applied by the farmer (green) and simulated by FAO-56 model (purple) during the farming season of 2002/2003 (between the 19th November 2002 and the 19th November 2003), at the 275 ha olive orchard located southeast of Marrakesh (Ezzahar et al., 2009). We also represent irrigation simulated by SiB2 for the same point during 2010 (red).

Figure 6: Hourly assimilation rate (μmol m^{-2} s^{-1}, Left axis), LAI (m^2m^{-2},Left axis, multiplied by 10 for illustration purpose), water stress (Unitless, Left axis, multiplied by 10 for illustration purpose), surface layer and root zone layer soil moisture content (percent of saturation (0–1), right axis), observed precipitation and irrigation ($mm.hr^{-1}$, right axis, divided by 10 for illustration purposes) and simulated surface runoff ($mm.hr^{-1}$, right axis, divided by 100 for scaling purposes).

Figure 7: Daily composite canopy assimilation and stomatal conductance in the selected grid cell, for all land cover types and for the weighted average, during (a,c) the growing season (FMA) and (b,d) outside the growing season (JJA).

Figure 8: Water budget components in the selected grid cell for all land cover types during (a) growing season (FMA) and (b) outside of the growing season (JJA). (dWg: variation of canopy and soil water store, Prec: total precipitation, Irrig: total irrigation, Roff: total runoff (surface runoff and gravitational runoff), Evap: total evapotranspiration). All components are in meters.

Figure 9: Daytime (a) and Nighttime (b) mean surface energy budget components over the study region for all vegetation types during the growing season (FMA): (rad1) canopy absorbed energy, (rad2) ground absorbed energy, (chf) canopy heat storage, (shf) soil heat storage, (hflux) total sensible heat flux, (ect) canopy transpiration, (eci) canopy interception loss, (egi) soil interception loss, (egs) soil evaporation. All components are fluxes and are in (W/ m^2).

Figure 10: Diurnal cycle of average surface temperature for all land cover type and the weighted average over the study region during the growing season (FMA) and outside of the growing season (JJA).

Figure 11: Maps of day and night time mean surface temperature over the study area during the growing season (FMA) and outside of the growing season (JJA).

Figure 12: Scatter plot of impervious surface area (ISA) versus daytime and nighttime mean surface temperatures during the growing season (FMA).

Figure 13: Surface temperature profiles across the city versus impervious surface area (%). Daytime and nighttime mean surface temperature during the growing season (FMA) and outside of the growing season (JJA) for 3 scenarios: 1- fully urban scenario (Red), 2- weighted average scenario-including urban (Black), 3- fully vegetated scenario – excluding urban (Green).

Figure 14: Monthly energy use (GW.h) versus observed mean surface air temperatures recorded during the years 2013 and 2014.