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Proposal Title : **Assessing the impact of urban land conversion on local and regional surface climate and its socioeconomic consequences in Western North Africa.**

SECTION VII - Project Summary

Urbanization represents a small areal fraction of global land transformation; however, it occupies earth's most fertile and productive lands, and its ecological impact is significant and long lasting on the landscape. Over the last few decades, urban expansion has been rapid and significant, especially in developing countries where the population is becoming increasingly urban and where changing land rights and ownership have led to expansion of suburban areas. Morocco, a developing country in Northwest Africa, is emblematic of these trends. Moroccan cities have high growth potential, particularly in terms of land use and verticality. However, urban policies in Morocco need improvement to accommodate the growing number of households forced to live in urban outskirts because of housing prices, and more generally to address environmental, economic, and social issues and regulate urban development as defined by the United Nations framework. Research on the specific physical processes associated with urbanization is needed to assess the impact of urban land conversion on local and regional surface climate and its impact on society. This research will help us understand the interactions between urban landscapes and surface climate and the relationships between urban land use and societies, and will provide managers and policymakers a knowledge platform to consider in urban planning.

Urban land conversion affects surface climate through four mechanisms: reduction of transpiration from a reduction in vegetation fraction; a reduction in water infiltration capacity and consequent increase in surface runoff; the alteration of surface albedo through choice of building material and color; and the modification of surface roughness and consequent impacts on surface heat and moisture convergence. The proposed research will use satellite data and models to address a core theme of this solicitation, namely that urban expansion has been rapid and significant over the last few decades, as populations in developing countries become increasingly urban. Specifically, the study comprises four major tasks:

First, we will use moderate-resolution optical imagery (Landsat, Sentinel-2) to map urbanization through time for the densely populated and rapidly urbanizing cities of Morocco. Specifically, we will generate maps for 10 large cities for two time periods -- 2008 and 2018 -- where data are available and where the urban signature is remotely measurable on the landscape. These products will serve as baseline boundary conditions for the modeling tasks. Second, we will run land surface models available through the NASA Land Information System (LIS) offline over the selected cities to assess the diurnal variation of the land surface temperature (LST) and evaluate the interactions between LST variability, city characteristics, and ambient climate. This modeling work will show which urban characteristics and related landscape arrangements are best for mitigating the UHI in cities with different climate settings. Third, we will use the fully coupled Weather Research and Forecasting (WRF) model to investigate the Urban Archipelago Effect (UAE) at a regional level over a group of relatively large cities along Morocco's Atlantic coast and assess the effect of the surface UHI on rainfall patterns. A key novelty of this research will be to explore the aggregate effects of an urban chain' generated by a series of large cities on regional climate. Finally, we will parameterize the urban-induced land cover and land use changes and their environmental effects to investigate building energy demand as calculated in the Global Change Analysis Model (GCAM).

Assessing the impact of urban land conversion on local and regional surface climate and its socio-economic consequence

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Table of Contents

I Statement of the Problem

Urban expansion has been rapid and significant over the last few decades, especially in developing countries where the population is becoming increasingly urban, and where changing land rights and ownership have led to expansion of suburban areas. Urbanization represents a small areal fraction of global land transformation; however, it occupies earth's most fertile and productive lands. Its ecological impact is significant and long lasting on the landscape, and the rate of land transformation is at least proportional to population growth and economic development. The rate and magnitude of urbanization varies widely across regions. For example, in the US, California, Texas and Michigan are the top three states in terms of urbanized lands, as characterized by the amount of Impervious Surface Area (ISA) circa 2011, while New York has the highest population [1] and a smaller urban footprint. It is therefore important that we understand the determinants of this type of land transformation, and its two-way interactions with its environment, so that future urban patterns can be planned and managed with multiple facets of sustainability in mind.

The conversion of forested and agricultural land to urban area alters vegetation phenology [2] and affects the carbon cycle [3,4,5]. Through these processes, urbanization affects hydrometeorological components [3,6,7] and climate [2,8]. For example, in the US, the conversion of agricultural productive lands to built-up land offsets the increase in Net Primary Productivity (NPP) from agricultural expansion, even though agricultural lands occupy 29% of the area whereas urbanized lands occupy only about 3% [4]. In a much less developed aspect of the research, Seto and Shepherd [6] described the role of urban environment on major climate systems. A key emerging issue included in their study was urban-precipitation-hydrology interactions and management. Since then, robust observational and numerical modeling studies providing evidence of urban-induced cloud, precipitation, and hydrological variability have emerged [7]. Further, urban jurisdictions are increasingly interested in managing or harvesting storm water for societal benefit [9].

Improving remote sensing characterization and dynamical modeling of urbanization and its biophysical impacts will improve our capability for both prognostic predictions and retrospective analysis in data assimilation. In addition, combined analyses with demographic and socio-economic data from census and surveys will advance our understanding of the vulnerability of the residents of cities to hydrometeorological changes and extremes and may suggest potential location-specific strategies for mitigation and adaptation of climate hazards.

The urban heat island (UHI), a well-documented urban phenomenon [8,10,11] is best illustrated in Quattrochi and Luvall [12,13,14], who used airborne thermal measurements to characterize urban heating over Atlanta, GA, USA. An observation-based study by Imhoff et al. [15] showed that in the US, the annual average UHI amplitude is 2.9°C with a remarkable asymmetry between summer and winter. However, in modeling the urban surface energy balance (USEB), Bounoua et al. [3,16] showed that, unlike in temperate climates where UHI is strong, this effect is not well marked in semiarid regions and that evaporative cooling from non-stressed vegetation surrounding urban areas is the primary driver of UHI. Li et al. [17,11] proposed a new method to quantify UHI and investigated the physical mechanism of UHI using the Weather Research and Forecasting-Urban Canopy Model (WRF-UCM).

In Morocco, a developing country in Northwest Africa, the last census of 2014 confirmed the polarization dynamics of the population around big cities. In 2014, the national number of houses amounted to 8.86 million units, of which 6.19 million (69.8%) were in urban areas. Seven cities accounted for 25% of the total population and for 41% of the urban population

[18]. This census also indicated that urban growth is mainly absorbed by cities' peripheries, which translates to urban sprawl. Population growth, economic development, and rural exodus indicators point to the intensification of this phenomenon in the coming decades, with a projected 70% increase in urban population by 2030 [19].

Moroccan cities have high growth potential, particularly in terms of land use and verticality, and future urban growth needs are estimated at 7000 ha/year by 2030 [20]. However, even Casablanca, the largest metropolis in Morocco, populated by about 3.5 million inhabitants, remains a medium-sized city compared to cities in other North African countries (for instance, Cairo and its suburbs hosts 21 million persons). With increase in size, cities induce stronger UHIs, which can impact human health and comfort. In Morocco, Johansson [21] showed that in a hot and dry climate, a compact urban design with deep canyons is preferable for the spatial structure of urban surface temperature, and Lachir et al. [22] showed that during the vegetation growing season, surface temperature was much higher in built-up areas than over other land cover types suggesting a contrast between build-up and vegetation. On the other hand, in the sub-humid region of Casablanca, Bahi et al. [23] found that daytime UHI appeared more important in winter than in summer and has gradually increased by more than 1°C in residential areas and in some small peri-urban towns from 1984 to 2015, suggesting a direct relationship between UHI amplitude and urban areas size. Fathi et al. [24] carried out the first evaluation of the UHI across several cities in Morocco and revealed a well-defined UHI in urban areas built on vegetated land and an Urban Heat Sink (UHS) in urban areas built in arid regions.

In Morocco, urban policies need improvement to address the increasing number of households pushed into urban outskirts by rising housing prices and the resulting destruction of already sparse forests. Despite efforts in territorial performance, urban planning is still not a widely adopted tool to address environmental, economic, and social issues and to regulate urban development as defined by the United Nations framework.

Research on the underlying causality of change through determination of the dynamic physical processes associated with urbanization is needed to assess the impact of urban land conversion on local and regional surface climate and its impact on society. Not only will this research help improve our understanding of the interactions between urban landscapes and surface climate, but it will also shed light on the relationships between urban land use and societies and will provide land-use managers and policy makers with a knowledge-platform about environmental and social implications, to consider when planning for cities.

II Background

Cities are central areas of economic productivity and are an efficient way for societies to live together and share resources, reducing the otherwise excessive land use. Therefore, the mode and typology of modern cities must be considered to maximize the positive benefits of urbanization, while minimizing the environmental cost. Strategies of urban development that only minimize a singular impact of urbanization in isolation, fail to minimize tradeoffs, leading to unintended consequences and feedbacks that can affect urban livability.

To date, there is no standardized definition of "urbanized land," and global maps representing this form of land use are rare, especially in developing regions. Defining urban areas based on administrative boundaries will disregard temporal updates and bias the assessment of changes. As such, there is a need for methodologies to identify urban lands and map them consistently to allow for objective intercomparison, at a spatial scale capable of resolving the urban metabolism and its impacts on the energetic, hydrological, and biological cycles as well as human health and comfort. Satellite data (e.g., Landsat, Sentinel and MODIS) provide an excellent resource to map urban areas and, in doing so, to study urban dynamics within the context of their surrounding environmental gradients, to evaluate their role in biology and hydrometeorology, and to provide an integrated ecological response.

Urban land conversion affects local and regional surface climate through four main physical mechanisms. The first involves the reduction of the fraction of vegetation and the subsequent reduction in transpiration, which is associated with warming. Urban land conversion also influences plant phenology within the urban perimeter and modulates the urban heat island (UHI). The second impact comes as a reduction in water infiltration capacity, due to impervious surfaces, and consequent increase in surface runoff. This may cause sudden flash flooding events with catastrophic consequences to people and properties. The third effect is the alteration of surface albedo through choice of building material and color, which has a significant impact on the surface energy balance. The fourth impact is through the modification of the surface roughness and its implication for surface heat and moisture convergence [8,28,29].

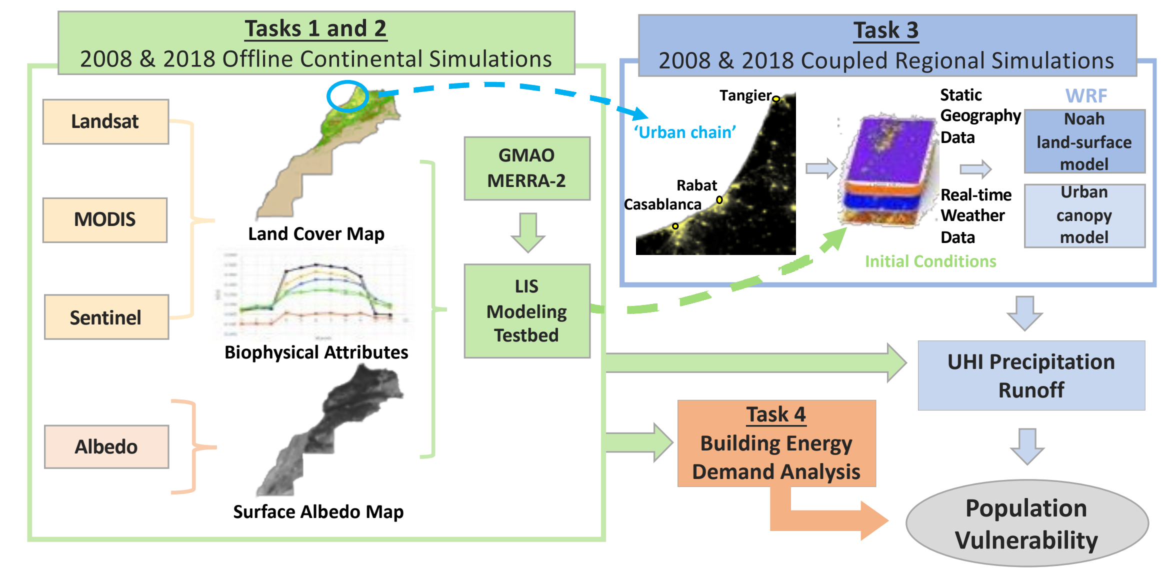


Figure 1. Schematic of the proposal objectives.

III Proposal Objectives

The objective of this research is to make extensive use of satellite data and models to address one of the core themes of this solicitation - namely that ***urban expansion has been rapid and significant over the last few decades, as populations in developing countries become increasingly urban****.* ***The focus is to identify high-impact LCLUC 'hotspots' over geographic areas in Morocco where human-induced LCLUC is occurring at a landscape scale of the order of 10,000 km²*****, and to evaluate the biophysical and societal impact of this LCLUC (Fig. 1).***

Specifically, we will carry out the following tasks:

III.1 - Mapping urbanization

Building on our previous work [8,11,16,17,22,25,26] we will apply machine learning-enhanced supervised classification techniques to moderate-resolution optical imagery (Landsat and Sentinel-2) to generate maps for 10 densely populated and rapidly urbanizing cities in Morocco for two time periods—2008 and 2018—where data are available to capture the urban signature remotely on the landscape. These 10 cities are LCLUC hotspots and are of national to regional importance, with significant impact and policy relevance. These maps will serve as the basis for our research and will be extensively validated using ground data and, where available, high-resolution commercial imagery (e.g., Planet, WorldView). We will use these moderate-resolution data to quantify the urban buildup and use the coarser MODIS data to characterize the surrounding vegetation and non-urban lands. For each of the two land cover maps, we will develop a set of biophysical parameters commonly required by land surface and climate models that address the earth system energetic, hydrological, and biological cycles.

We will then use these land cover maps along with the derived biophysical parameters in a and perform simulations for each of the two years (2008 and 2018), thereby generating surface climate variables at scales ranging from hourly to annual at landscape levels. Finally, we will use these climate variables to quantify the biophysical impacts of urbanization, study the consequences of these biophysical changes on runoff and energy demand, and ultimately evaluate the role of urbanization on population vulnerability (Fig. 1).

III.2 - Urban heat island (UHI) modeling and analysis

Using the land cover maps and biophysical parameters from Task 1 as inputs, we will perform simulations of Land Surface Models (LSMs) available in the NASA Land Information NASA Land Information System (LIS) modeling system [27] over the selected cities for each of the two years (2008 and 2018). We will use these simulations to assess the impact of different urbanization patterns on the diurnal variation and spatial distribution of the land surface temperature (LST). We will explore the dynamic relationships between the cities' spatial characteristics—such as size and morphology—and the UHI and relate the UHI amplitude to each city's morphology and ambient climate. We will characterize the LST diurnal cycle for distinctive cities and assess the specific influence of each plant functional type on surface temperature. This modeling work will show which urban characteristics and related landscape arrangements are best for mitigating the UHI in cities with different climate settings.

III.3- Regional modeling of the 'Urban Chain' effect

The biophysical impacts of urbanization can extend beyond local UHI to regional climate, especially when cities are arranged in large, spatially contiguous clusters. For example, recent work in Japan has shown that "archipelagos of cities can have an amplified effect on climate" [46]. However, no robust study has been conducted on this effect in any other climate. The Moroccan mid-Atlantic 'urban corridor' (Fig. 2) is ideal for such a study of the aggregate effects of an urban chain' generated by a series of large cities on regional climate. To that end, we will perform

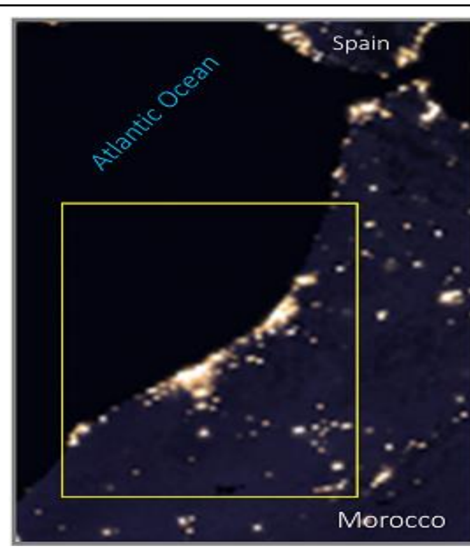


Figure 2. VIIRS nighttime lights showing cities in Morocco. The yellow box represents the regional modeling domain.

simulations of the fully coupled Weather Research and Forecasting (WRF) model at a regional level over a group of relatively large cities along Morocco's Atlantic coast to investigate the impact of urbanization on regional mesoscale weather and seasonal climate for the years 2008 and 2018. These simulations will provide insights into the impact of urban land conversion on the surface thermal signature and the atmospheric chemistry profile, the upward diffusion of both through the atmospheric boundary layer, the sensitivity of this diffusion to city typologies and the spatial arrangement of cities within a region, and the consequences of these effects on precipitation and cloud formation.

III.4-Socio-economic building energy demand response

We will parameterize the urban-induced land cover and land use changes and their environmental effects to investigate building energy demand as calculated in the Global Change Analysis Model (GCAM) [30,31]. We will combine the spatial distribution of changes in temperature and floorspace in response to urbanization and the UHI effect with estimates of building shell conductivity, income, and satiation levels to evaluate changes in building energy heating and cooling demands. We will also investigate the implications of shifts in building energy demands on electricity generation and emissions.

IV Responsiveness

This research is responsive to the solicitation theme: urban expansion has been rapid and significant over the last few decades, as populations in developing countries become increasingly urban. This research specifically responds to the need for identification of high-impact LCLUC hotspots—areas where the human-induced land cover change is occurring at a landscape scale (~10,000 km^2). The focus of the research is on those LCLUC changes that have a significant impact in terms of ecosystem services and societal relevance. Use of established NASA Earth Observing System data (MODIS, Landsat, Sentinel) is an essential

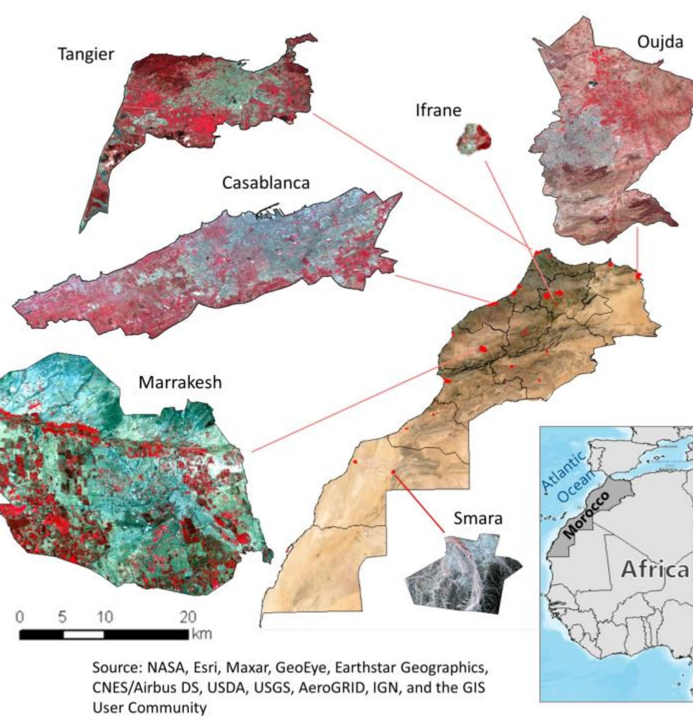


Figure 3. Example of cities hotspots that will be examined.

component of this work, and, where available, we will also take advantage of commercial data available through NASA's Commercial Smallsat Data Acquisition (CSDA) program. Finally, the work leverages NASA modeling capabilities through the use of the Simple Biosphere (SiB) model and Land Information System (LIS).

V Methodology

V.1 Region of interest

The region of interest is Morocco, a country in Northwest Africa. This research will contribute towards the international program Global Observation of Forest Cover and Land Use Dynamics (**GOFC-GOLD**) through the regional network - North Africa Research Initiative (NARI) coordinated by collaborator Dr. Bounoua from the US side and by Dr. Bahi from the Moroccan side. Algorithms and data from this proposal will feed into the GOFC-GOLD program and its regional networks.

The region of interest will include 10 cities where large LCLUC has been observed during the study period (2008–2018). These cities were selected based on relevance to the proposal focus and include cities of varying sizes, physical geographies (coastal, interior, mountainous), and climatic zones (ranging from temperate-humid and sub-humid to arid and hyper-arid). Figure 3 shows the study region and a subset of cities that will be studied.

V.2 Specific Tasks

This project comprises four major tasks that, collectively, seek to provide a comprehensive understanding of the effect of urban land conversion on the local and regional climate over Morocco.

Task 1 - Generation of land cover maps and biophysical attributes

Task 1.1: Mapping urbanization

We will combine moderate-resolution data from Landsat at 30m and Sentinel-2 at 10-20m to map rapidly urbanized cities, discriminating urban surfaces from other land cover types (e.g., vegetation, water bodies, bare soil, and sand) over 10 cities in this semiarid region in Northwest Africa at 30m spatial resolution. We will use machine learning-enhanced supervised classification approaches with inputs that include both spectral (e.g., tasseled cap greenness) and temporal (e.g., vegetation phenology) features. Our training dataset will primarily rely on expert opinion and extensive in-situ data collection from our collaborators in Morocco. These training data will include the location of the cities, as well as polygons delineating their peripheries. Where available, we will perform additional validation based on analysis of

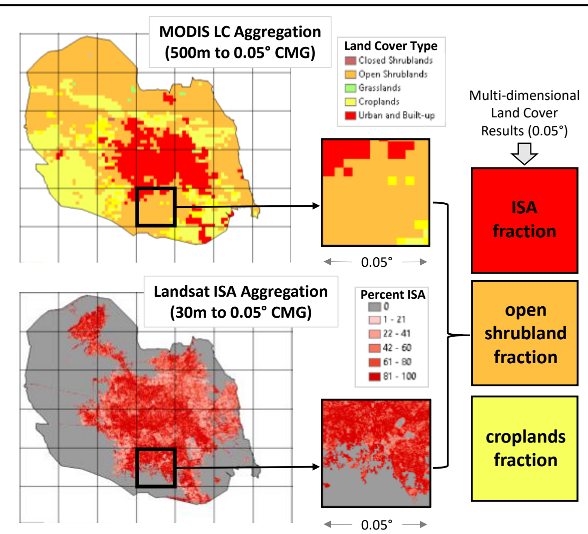


Figure 4. Illustration of the conversion of LC dataset to CMG (see text for details).

imagery provided through the NASA Commercial Smallsat Data Acquisition program (CSDA; e.g., Planet, WorldView). At the end of this task, we will have two accurate maps of the urban area for 2008 and 2018, represented by their impervious surface area (ISA) over 10 cities of different sizes, macroforms, and ambient climates. For the 2018 map, we will reinforce our machine learning-enhanced supervised classification with the European Satellite Agency (ESA) Climate Change Initiative (CCI) 20-meter Land Cover dataset to distinguish impervious surfaces area (ISA) from other natural surfaces [32].

For each of the years, we will combine the ISA data from the cities with corresponding MODIS land cover data at 500m (MCD12Q1) collection 6 and aggregate it to a common Climate Modeling Grid (CMG) at 0.05° (~5km x 5km) over the city limits (Fig. 4). MCD12Q1 land cover is available globally from 2001 to 2020 at a yearly interval (https://lpdaac.usgs.gov/data). The MCD12Q1 classification uses the dominant type to produce 15 distinct cover types including a build-up class [33]. The proposed data fusion will be done as follows: (1) aggregate the different land cover types existing in the 500m MCD12Q1 to obtain fractions in the CMG [1]; (2) aggregate the Landsat ISA from 30m to 0.05° and co-register them to the CMG; and (3) impose the aggregated Landsat ISA fractions as ground-truth into the CMG. When imposing the Landsat ISA into the CMG, differences between the ISA fraction obtained from Landsat and the build-up fraction obtained from MODIS will be redistributed over other cover types co-existing in the CMG. The redistribution will be weighted by the fractions of the existing cover types. In cases where the build-up class from MODIS is 100%, the difference will be distributed over non-urban cover types imported from surrounding grids in the immediate vicinity. The reconstructed product will provide a multidimensional land cover map at 0.05° nominal resolution including fractions of ISA from Landsat and fractions of land cover types co-existing in the CMG from MODIS. We will also use the MCD12Q1 as a mask to average the MODIS Normalized Difference Vegetation Index (NDVI) over each of the MODIS co-existing vegetation classes in the CMG. The urban NDVI will be derived from Landsat data. Figure 4 shows an example of a CMG with fractional land cover types and average NDVI, which shows the urban area with a small amplitude annual cycle (see also [3]).

Task 1.2: Generating biophysical attributes

Most land surface models (LSMs) that model the surface energy budget (SEB) require an a priori knowledge of the leaf area index (LAI), the fraction of photosynthetically active

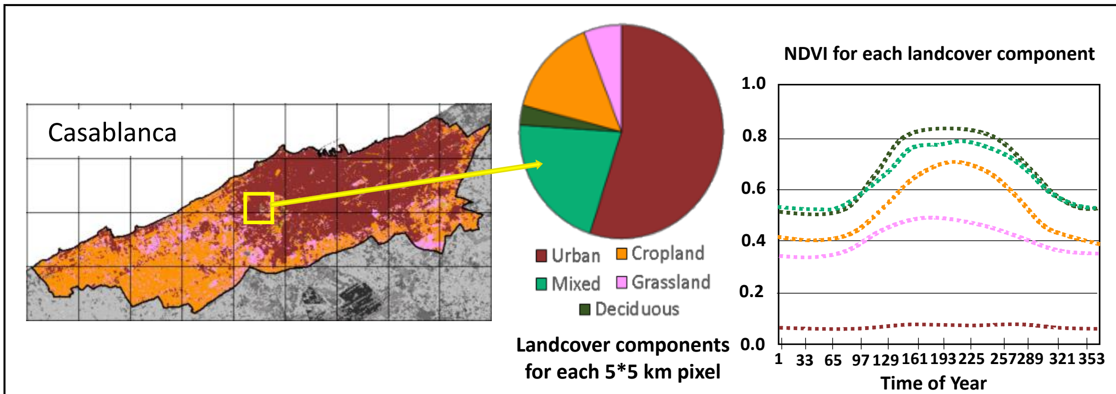


Figure 5. Example of fractional land cover and average NDVI

radiation (FPAR), the greenness fraction (G), an initial bulk aerodynamic resistance of the vegetation (R_S), the roughness length (Z_0), the zero-plane displacement (dd) and the surface snow-free albedo (SFA) for all land cover types co-existing in the CMG. FPAR, LAI and G are derived directly from NDVI data and are land cover type-dependent [16,34], while R_S, Z_0, dd, and SFA are derived from functional relationships based on satellite-derived observations and land cover-dependent properties such as leaf reflectance in different regions of the spectrum. These attributes are not part of any data production project and will be calculated separately as part of the models' pre-processing using the land cover maps and NDVI developed in Task 1.1 along with other observed vegetation-dependent morphological, optical and physiological properties [34]. For these calculations, the urban class will have the characteristics of a bare soil cover-type, but its physiological, optical and morphological properties will be modified [3]. Urban classes will be assigned the lowest NDVI value obtained from Landsat [35], the lowest photosynthetic capacity [3], a snow-free soil reflectance determined from Landsat, and high and rough surface elements (i.e. Z_0). For each of the two land cover maps, this task will produce distributed annual time series of spatially and temporally continuous biophysical parameters at an 8-day interval for each land cover type co-existing in the CMG (Fig. 5).

Task 1.3: The urban albedo

For all vegetation fractions in the CMGs, the surface albedo will be derived from MODIS products (Fig. 6). However, for urban areas, we will use multi-channel Landsat data to derive a map of surface albedo in the visible (VIS) and near infrared (NIR) wavelengths [35] for use in the urban-canopy model of the LSMs. Surface albedo is an essential factor influencing the urban surface energy balance (USEB), with low albedo absorbing more solar energy and resulting in high surface temperature.

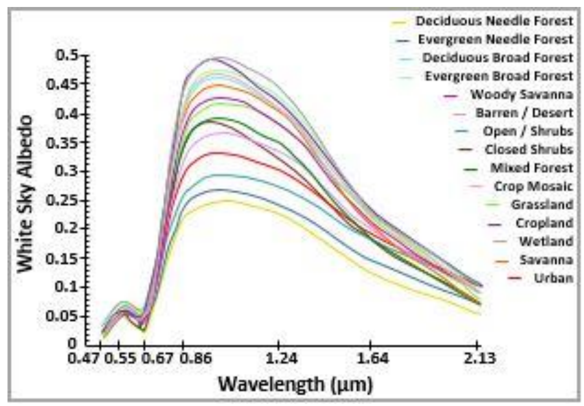


Figure 6. MODIS albedo (July 2001) over Chicago for different land cover classes.

Various products [9] have been developed to enhance solar reflectance so that UHI effects are mitigated, and air-conditioning loads are reduced. Such products include high reflectance paints, high-performance glass and window films [36]. The use of high reflectance paint on roof surfaces has been found effective to improve the indoor thermal environment during summertime [37]. Similarly, the use of high reflectance paint has been shown to reduce the temperature of pavement in roads. The distinctive spectral selectivity of these products enhances the reflectance sharply in the near-infrared region of the spectrum. However, there is limited research assessing the behavior of high reflectance materials with a spectral selectivity in the urban environment. We will carry out an extensive validation of the Landsat-derived albedo in urban areas using observations from different sources over selected target urban areas. These observations include multi-year albedo measurements for black, white and vegetation roof membranes [9,38] and for multiple membrane types, plants and technologies for each of these surfaces. An example in Figure 7 shows that the fresh surface lost almost half its albedo in two years due to weathering and atmospheric deposition in an urban environment.

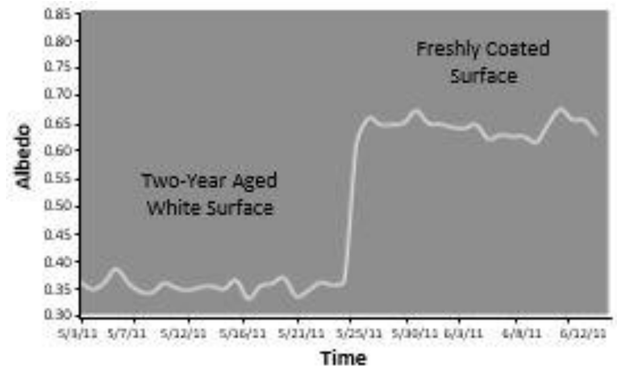


Figure 7. Albedo change for a freshly painted white elastomeric paint applied to an asphaltic roof in New York City [9].

Task 2: Urban heat island (UHI) modeling and analysis

Using validated land cover maps and the biophysical parameters obtained from Task 1, we will run LSMs at the plot level for calibration over CMGs in select cities and validate the model's surface temperature against observed LST from Landsat available on the Earth Explorer data portal (https://earthexplorer.usgs.gov/). Point data are available for the cities of Tangier, Casablanca, Ifrane, Marrakech and Smara located in different climates zones. Moreover, heat conduction, water hydraulic capacities and soil porosity will be obtained from look-up tables averaged over aggregates of concrete, asphalt, or roof material. After validation over several points, we will extend the LSMs runs to the selected cities and assess their performance in describing the USEB in different ecoregions and regional climate regimes. We will run several biophysical LSMs available under NASA's Land Information System (LIS) (http://lis.gsfc.nasa.gov/) using the products derived in Task 1. LIS is a multi-scale testbed for land surface modeling and data assimilation studies. The system employs a suite of LSMs and provides a means to execute them using satellite and ground-based observations within a high-performance computing environment. The flexibility of the LIS framework allows it to run LSMs using different data sources and under different spatial and temporal resolutions, as such it is suitable for local and regional scale simulations. LIS is also used offline to produce initial conditions for the WRF model with an Urban Canopy Model, the NOAH-UCM. Among the several LSMs in the LIS, some already include urban algorithms with varying complexity, such as the modified Simple Biosphere model SiB2 [34] as modified by Bounoua et al. [3], the Community Land Model (CLM) [39,40], and the NOAH-UCM [41]. These LSMs were validated and have been proven capable of describing the land surface water, energy and carbon budgets with a reasonable degree of confidence [3,16,22,42,43,44,45] and will be further validated in this project under this task.

We will employ these LSMs to carry out simulations using each of the land cover maps and the derived biophysical attributes developed in Task 1. We will run LIS offline (i.e., drivers fed from observations) using climate drivers at a 5 km x 5 km grid and an hourly time step to capture the effects of surface heterogeneities at scales ranging from diurnal to annual. We will also make use of the ability of LIS to perform computations on tiles ("mosaic approach") within each 5 km x 5 km CMG to retain the higher resolution of the land cover and biophysical

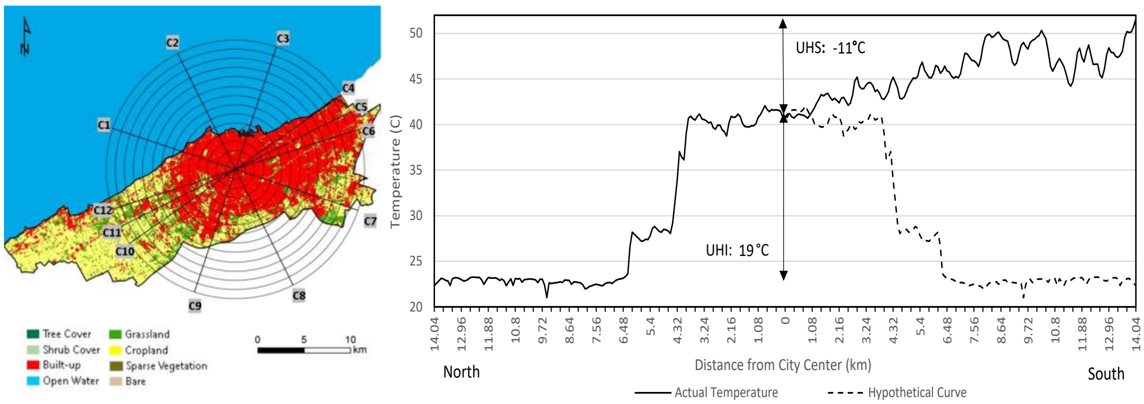


Figure 8. Land cover classification for the urban area of Casablanca with buffer circles shown every 1080m (left), and average surface temperature cross section perpendicular to the coastline and across the city of Casablanca, obtained over axes C1-C3 for the northern periphery and C7-C9 along the southern periphery. The dashed line represents a hypothetical temperature obtained by symmetry from the northern part.

information. Fluxes (e.g., evaporation) and states (e.g., temperature) variables will be computed for each land cover fraction and then aggregated to CMG at each time step. However, individual fraction contributions as well as weighted aggregates will be saved at each time step (hourly) to generate detailed outputs within and outside selected urban areas. The LIS modeling system will be run forward for one year after a spin-up of three consecutive years. We will use the 2005-2007 forcing to spin-up the 2008 simulations and 2015-2017 to spin-up the 2018 runs. We will select the NASA Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) data to drive the LSMs. MERRA-2 is a long-term global reanalysis to assimilate space-based observations. The spatial resolution is 1/2° latitude by 5/8° longitude with an hourly temporal resolution, downscaled on the fly in the LIS system.

Results from different urban areas will help understand the surface temperature diurnal response to ISA in the city core as well as along settlement patterns (e.g., urban core to pre-urban to peri-urban to rural). The results will describe the structure of the surface temperature across and within cities and may help define ways to mitigate the UHI through a better choice of construction material properties such as heat absorption and reflectance paints, building orientation and height, fraction of vegetation, and water bodies. A combination of these land elements will be of great help to alleviate the urban excess heating. The difference in urban land extent between the two years will be related to surface temperature change and the UHI amplitude for each of the different cities to segregate the impact of size, elevation, macroform and ambient climate on the formation, amplitude, and the diurnal cycle of the UHI. The analysis will also explore the amount of carbon sequestration lost to urbanization and the ratio of runoff to precipitation as a function of urban density [8].

This work complements an ongoing effort by our Moroccan collaborators and expands it beyond a diagnostic analysis. For example, Figure 8 shows a temperature cross-section perpendicular to the coastline in Casablanca and reveals a formidable UHI with an amplitude of 19°C in the northern periphery but shows an urban heat sink (UHS) in the southern part where the temperature continues to increase from 41°C in the city center to 52°C in the southern outskirts.

We will analyze the surface temperature structure and compare the UHI between the different cities and explore its structure within the city as it varies between vegetated residential and industrial neighborhoods. We will characterize the LST diurnal cycle for distinctive hotspots and assess the impact of each plant species on surface temperature. This modeling work will reveal an arrangement of land surface elements that effectively reduces the UHI effect in cities with different ambient climates.

Task 3 - Regional mesoscale modeling of the 'Urban Chain' effect

Having isolated and quantified the impact of urban land conversion on land surface biophysical states and fluxes, we will then evaluate the fully coupled urban canopy-atmosphere interactions. Specifically, we will run a coupled regional simulation to explore the individual and collective impacts of cities arranged in an 'urban-chain' along Northwestern Morocco. The urban archipelagos effect (UAE) formed by major cities along the northwestern coast of Morocco is unique and, to date, no modeling study with a fine spatial resolution capable of resolving the urban morphology has assessed its impact on the regional climate beyond a study in Japan [46]. The literature on urban modifications to dynamical flow, temperature, and precipitation is conclusive [7,10]. Many other studies have also described the two-way interactions between cities and their environments [47,48,49]. However, no comprehensive study has approached this unique organization of urbanized lands from the standpoint of an urban aggregation acting on the Moroccan regional climate.

We plan to run the WRF model with the NOAH-Urban Canopy Model (UCM) with the consideration of urban scale morphology to investigate the impact of urbanization on regional mesoscale weather and seasonal climate for the years 2008 and 2018. The WRF-model setup will follow closely the setup in Li et al., (2018) with urban parameters obtained from Moroccan cities. Three nested domains with horizontal grid spacing of 15 km, 3 km and 1 km will be used with 35 vertical levels. The critical parameters of UCM, including morphological parameters, imperviousness of urban land cover, anthropogenic heat emissions, optical parameters, and thermal parameters, will be updated for the Moroccan cities from multiple sources datasets.

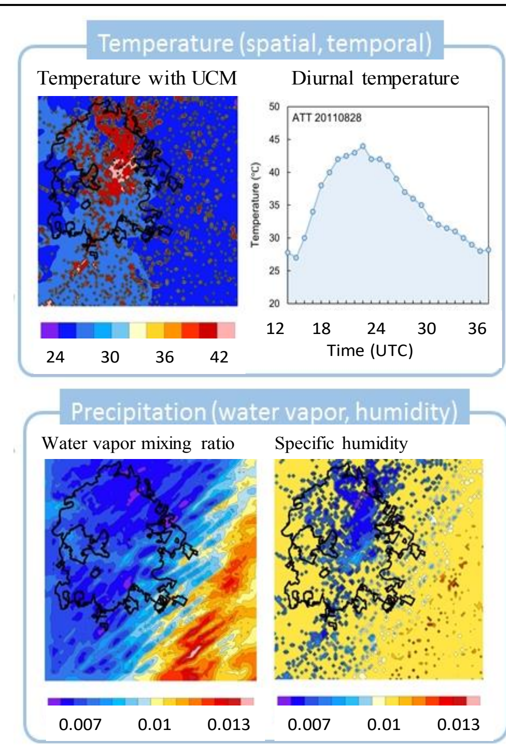


Figure 9. Example of WRF simulation for Austin, (TX) during summer [46].

Such simulations will provide insights into how the UAE modifies the atmosphere's thermal and dynamical structure and will quantify in detail the impact of urban land conversion on the surface thermal signature and its upward diffusion through the boundary layer. They will also help to understand the impact of urban land conversion on precipitation (frequency and magnitude) and overland runoff upwind and downwind urban centers. Since the region includes several urban areas with high air pollution, we will consider the effect of aerosols on cloud formation in our simulations. WRF is set with an aerosol module that will be modified to the region's characteristics. Aerosol data are available from the GMAO (https://fluid.nccs.nasa.gov/cf/classic_geos_cf/).

Figure 9 shows an example of temperature and precipitation outputs from the WRF-UCM model. The predicted structure will be compared to the dynamical direct thermal circulations and/or chain flows described in Ohashi and Kida [46]. A comprehensive inter-cities comparison will be performed for the surface and atmosphere thermal structure, the precipitation frequency and magnitude, as well as overland runoff.

A comprehensive validation of these simulations will be performed using precipitation data from TRMM, GPM, and the National Oceanic and Atmospheric Administration (NOAA) multi-sensor precipitation estimates as well as MODIS LST. The model will also be validated against available urban weather stations [24] for surface temperature and meteorological data to be provided by collaborators from the Direction de la Meteorologie Nationale (DMN) . In the city of Casablanca, we will validate WRF outputs against the urban meteorological database collected on several stations spanning most of the neighborhoods and include standard weather variables. These are all stationary fixed points that can be used as targets for WRF simulations to evaluate its performance at simulating intra-city variability.

Overall, the 2008 and 2018 conditions will be used to assess trends in urban ISA and changes in simulated precipitation, dynamical flow and temperature that will be compared to observations and to previous work [50]. The regional scale simulations with varying complexities of urban land cover (e.g., full archipelago, no archipelago, archipelago without specific cities) will lead to transformational findings. We are particularly interested in evaluating whether an integrated or cohesive response to the "chain of heat islands" is found in the mid-tropospheric climate variables as suggested by Ohashi and Kida [46] for Japan.

We will frame our analysis around five landscape typologies: (1) sprawl, (2) high-density urban, (3) urban shape represented by the area to perimeter (A/P) ratio, (4) building height, and (5) the urban chain archipelagos. Because of computing resources, we will limit our modeling domain to be small enough to allow for mesoscale resolutions, yet large enough to represent the five selected typologies at a range of 5kmx5km. WRF simulations will then be run for high-impact (e.g., heat waves; 3-7

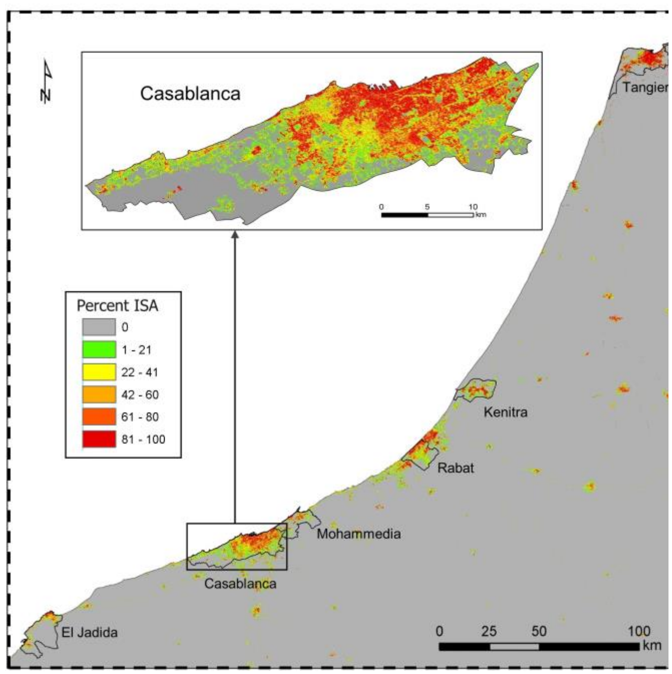


Figure 10. Study cities with different landscape typologies. Dashed rectangle represents WRF's outer domain.

days) and seasonal (e.g., 3-4 months). We will include cities along a meridional transect with a sensible climatic gradient and belonging to the same ecoregions, such as El Jadida, Casablanca, Mohammadia, Rabat and Tangier (Figure 10). We select the Casablanca metropolis for urban sprawl, Rabat for high density urban, and building height, Mohammadia for clumpiness, Tangier for fragmentation and the Casablanca, Mohammadia, Rabat corridor for the urban-chain effects. Note that Casablanca and Rabat have different shapes and therefore different area to perimeter ratios (A/P) and will provide an objective basis for comparing our modeling results.

Task 4: Socio-economic building energy demand response

For this experiment we will investigate how the UHI-induced changes in local near-surface temperature (calculated in Task 2) interact with changes in floorspace affect building energy demand. We will use the methodology used in the Global Change Analysis Model (GCAM) as documented in several past studies [30,31,51,52]. The methodology we will use breaks the building sector into three energy services—heating, cooling, and "other" services—which allows us to investigate the temperature impacts independently of "other" services such as cooking, lighting, refrigerators, and televisions. The building energy demands for heating and cooling per unit of floorspace will be calculated as shown in equations 1 and 2 below, where d_H and d_C represent the energy demands for heating and cooling respectively. Each of these equations can divided into three components shown in different colors in the equations and described subsequently.

$$d_H = k_H \times (HDD \cdot \eta \cdot R - IG) \times \left[1 - \exp\left(-\frac{\ln 2}{\mu_H}\frac{i}{P_H}\right)\right] \tag{1}$$

$$d_C = k_C \times (CDD \cdot \eta \cdot R - IG) \times \left[1 - \exp\left(-\frac{\ln 2}{\mu_C}\frac{i}{P_C}\right)\right] \tag{2}$$

where
H = Heating
C = Cooling
d = Energy demand per unit of floorspace (GJ/m^2)
k = Unitless calibration coefficient
HDD = Heating degree hours (hour °C)
CDD = Cooling degree hours (hour °C)
η = Thermal conductance (GJ/m^2 hour °C)
R = Unitless average surface-to-floor area ratio
IG = Internal gain [GJ/m^2]
μ = Region and sector specific demand satiation
i = Per-capita income
P = Total price of service (Weighted average of technologies used)

The first component, shown in blue, represents a calibration parameter (k), that can be calculated for each region of interest. This parameter can be thought to characterize the ratio of a "satiated heating and cooling demand" term (i.e., without economic constraints) for a chosen calibration year, to the local temperature and building characteristics for that year. This is calculated by first setting the per capita income (i) to infinite which results in the purple part of the equation (representing the economic effect) being removed. The service demands for heating and cooling as well as the remaining elements of the equation are then set for a chosen base year and the k_H and k_C parameters calculated accordingly.

The second component of the equation, shown in orange, represents the impacts of changes in temperature as well as any changes in building characteristics. Heating Degree Days (HDD) and Cooling Degree Days (CDD) are defined as the summation of temperature differences from a subjective reference temperature (set to 65°F, or 18°C) based on the methodology used by National Ocean and Atmospheric Administration (NOAA) [53]. These are typically calculated for each month using the day as a baseline unit but can also be adjusted to be used for any time period (e.g., Heating Degree Hours (HDH) and Cooling Degree Hours (CDH), [30]). For this work, we will calculate these metrics from near-surface air temperatures estimated in Task 2. This component of the equation also represents certain building characteristics captured in the terms: η representing the building shell conductivity; the term R representing the ratio of floorspace to building area; and the term IG representing the internal gains associated with the heat released by "other" energy services such as appliances.

The third and final component in (purple) represents the economic effects on the demands. It indicates the fraction of the "satiated demand" (described earlier) that is achieved, which increases with the affordability of the services. The affordability is measured as per capita income divided by the price of the service (weighted average of the estimate of technologies being used). Therefore, affordability and, consequently, service demands increase if per capita income increases or if the price of the service decreases. The μ parameter is the satiation impedance, and it represents the level of affordability required to achieve half the satiation. This is the second calibration parameter and similar to k, is calculated based on the per capita service demand and the affordability (per capita income and service price) in the chosen calibration year.

The heating and cooling building energy demands will be calculated and combined with the estimates for changes in total floorspace in response to urbanization and urban expansion. Finally, the relative increases in building energy demands will be compared to total energy demands and emissions for the region in order to estimate implications on energy generation and corresponding emissions.

VI Expected Outcomes and Deliverables

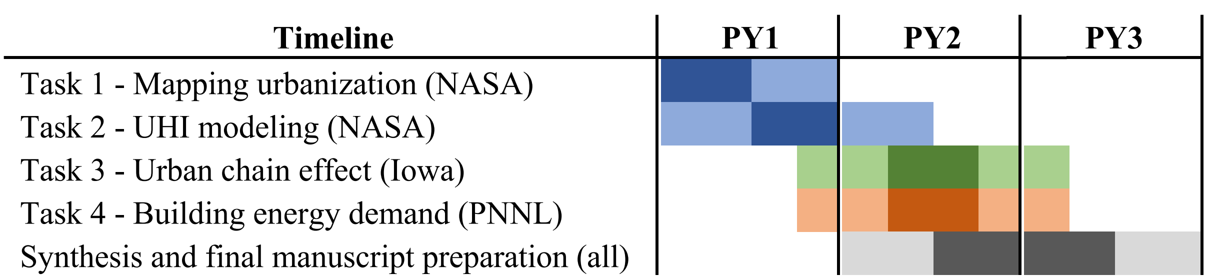
The study will develop land cover maps for the selected cities discriminating between the impervious surfaces and the different land cover types surrounding them. These maps will be used in models to assess the impact of the land cover change on surface climate variables and consequences on society. We will publish at least one peer-reviewed manuscript on our validated urban land cover maps in a remote sensing journal such as *Remote Sensing of Environment*; this manuscript will include a thorough description of our urban land cover mapping algorithm and ground validation, quantitative results about changes in urban land cover between 2008 and 2018, and broader conclusions about urbanization trends in Morocco and their implications.

Inter-cities comparison of UHI will be evaluated and related to typology and local ambient climate, an important determinant of buildings' energy consumption. Intra-city analysis of UHI will be conducted using observed and modeled LST to explore the distribution of heat-sources and sinks among neighborhoods in the same city and characterize them in terms of morphological (architecture and building types) and optical properties (color and nature of building material). The WRF modeling will provide an analysis around four landscape typologies: (1) sprawl; (2) high-density urban, (3) urban shape represented by the area to perimeter ratio and (4) the urban chain archipelagos. We will prepare at least one peer-reviewed manuscript describing our modeling approach and resulting understanding of the biophysical and climatic impacts of urbanization at local and regional scales in Morocco in an environmental science journal such as *Environmental Research Letters*.

Finally, our proposed research will also include socio-economic implications of changes in population, urbanization related floorspace expansion and UHI-related temperature shifts on heating and cooling energy demand response in buildings. The results will allow us to broaden and improve our understanding of these feedback pathways between urbanization and climate and their effects on energy demand response from urban residents with corresponding shifts in electricity and emissions. We will describe the methods and results of this work in a peer-reviewed manuscript in *Energy Economics* or a similar journal with a socio-economic focus.

VII Responsibilities and timeline

Dr. **Shiklomanov, PI**, is an expert in land surface modeling and remote sensing applications for vegetation-climate feedbacks. Dr. Shiklomanov is also well-acquainted with coupled human-natural systems processes in general and specifically how they are represented in GCAM through his past work at the Pacific Northwest National Laboratory. Dr. Shiklomanov will oversee the project, coordinate activities between co-investigators and collaborators, and lead Tasks 1 (land cover mapping) and 2 (SiB2 modeling). **Dr Zhang, Co-I**, is an expert in the urban heat island and its environmental impacts, including the data source, quantifying methods, drivers, and effects, and simulation thereof using the WRF model. Dr. Zhang will be responsible for staging and running the WRF model, as described in Task 3. **Dr. Khan, Co-I**, is an expert in coupled Human-Earth System modeling in general and specifically in the relationship between climate and energy demand and its representation in GCAM. Dr. Khan will be responsible for characterizing building energy demand response, as described in Task 4. **Dr. Bounoua, Collaborator**, is a senior NASA scientist with expertise in land cover land use change, land surface modeling, including urban areas, and has extensive experience working with Moroccan scientists. He will help with the running of SiB2 and analysis of the offline simulations. Dr. Bounoua will be the link between the US and Moroccan collaborators **H. Bahi** and **Dr. Yacoubi**. Collaborator Bahi is an expert in urbanization and remote sensing thereof in North Africa and will use this expertise to provide guidance on analysis and interpretation of results in all Tasks. Dr. Yacoubi will provide unfunded supervision of the ground validation activities described in Task 1.



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Data management plan

To the extent possible, we will perform every aspect of this work in open and publicly available virtual spaces. We will perform all code development for this project in publicly available GitHub repositories, thereby making not only the final result but the entire development process transparent. The satellite data to be used for the proposed work are already publicly available through the NASA EarthData portal, but we will develop our scripts for downloading and processing these data in public GitHub repositories. In addition, we will archive all derived data products produced by this work—including land cover maps, training datasets, and model simulations—in one of the NASA Distributed Active Archive Center (DAAC), selected based on consultation with DAAC staff and the LCLUC program management (candidate DAACs include the Socioeconomic Data and Applications Center, SEDAC; Oak Ridge National Lab DAAC, ORNL DAAC; and Land Processes DAAC, LP DAAC).

We will store all derived raster imagery datasets in Cloud Optimized GeoTIFF (COG) format, a widely used analysis-ready format with robust programming language support (through the GDAL library) and which can be readily ingested into desktop (e.g., QGIS, ArcGIS) and cloud-based (e.g., Google Earth Engine) GIS software. We will store vector datasets in GeoJSON format, selected because it is self-contained, self-documenting, well-supported across GIS applications, and is both human- and machine-readable. We will distribute model outputs in formats based on their size and complexity — small datasets in CSV format, gridded 2D datasets in COG format, and multi-dimensional datasets in NetCDF format. Based on investigators' previous experience performing similar analyses, we estimate that the total data volume of this final archived package to be on the order of 10-20 GB.

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Appointments

2020 – Present:	Research Physical Scientist, NASA GSFC Biospheric Sciences Laboratory (618)
2018 – 2020:	Postdoctoral Research Associate, Joint Global Change Research Institute (JGCRI), Pacific Northwest National Laboratory (PNNL)

Relevant Experience

Dr. Shiklomanov's research focuses on understanding, quantifying, and reducing uncertainties in land surface model projections of vegetation-atmosphere interactions. He is particularly interested in the development and applications of model-data fusion techniques for calibrating and validating model projections against a variety of observations, including satellite remote sensing, field spectroscopy, plant trait measurements, forest survey data, and meteorological towers.

Education

- Ph.D., Boston University (2018), Geography, College of Arts and Sciences
- Honors B.S. with Distinction, University of Delaware (2014), Chemistry, College of Arts and Sciences; Environmental Science, College of Earth, Ocean, and Environment

Selected Professional Service

- Oak Ridge National Laboratory Distributed Active Archive Center (ORNL-DAAC) User Working Group
- NASA Surface Biology and Geology, Algorithms and Modeling working groups
- Ecological Forecasting Initiative, Cyberinfrastructure and Methods working groups

Selected Relevant Publications

- **Shiklomanov, A. N**., Dietze, M. C., Fer, I., Viskari, T., & Serbin, S. P. (2020). Cutting out the middleman: Calibrating and validating a dynamic vegetation model (ED2-PROSPECT5) using remotely sensed surface reflectance. *Geoscientific Model Development*, 14(5): 2603–2633.
- **Shiklomanov, AN**, Bond-Lamberty, BL, Atkins, JW, Gough, CM. (2020) Structure and parameter uncertainty in centennial projections of forest community structure and carbon cycling. *Global Change Biology* 26(11), 6080-6096.
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- **Shiklomanov, AN**, Cowdery, EM, Bahn, M. Byun, C., Jansen, S., Kramer, K., Minden, M. et al. (2020) Does the Leaf Economic Spectrum Hold within Plant Functional Types? A Bayesian Multivariate Trait Meta-Analysis. *Ecological Applications* 30(3): e02064.
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Education

2017 Comillas Pontificial University - Spain, TU Delft - Netherlands, KTH – Sweden. Erasmus Mundus Joint Doctorate, PhD in Sustainable Energy Technologies and Strategies (SETS).
2010 Cornell University, NY, USA. Master of Engineering (Geotechnical)
2009 COMSATS Institute of Information Technology, Pakistan. Master of Project Management
2007 Dartmouth College, NH, USA. BA – Engr./Environmental Studies with Earth Sciences

Appointments

2020 - Present Computational Scientist, Joint Global Change Research Institute, PNNL
2018 - 2020 Post Doctorate RA, Joint Global Change Research Institute, PNNL
2017 - 2018 Research Assistant, International Institute for Applied Systems Analysis (IIASA)

Research & Education Interests:

- Research involves modelling and analyzing global interconnected human and earth systems with a focus on developing tools and methodologies to promote stakeholder engagement and facilitating the analysis of global modeling outputs in the context of local issues. Recent work focuses on the analysis and visualization of global modeling outputs at finer decision relevant spatial and temporal scales.

Professional Affiliations

- American Geophysical Union; European Geophysical Union

Selected Honors & Awards:

- 2015 IIASA YSSP Fellowship; 2015 AEEE Conference 2015 Young Researcher Award; 2013-2017 Erasmus Mundus Joint Doctorate Fellowship**,** SETS, Category A; 2007 Richard D. Lombard Public Service Program Fellowship; 2003-2006 STARR Scholarship.

Selected Publications (of 26 total)

Khan, Z., Wild, T.B., Iyer, G.C., Hejazi, M. and Vernon, C.R., 2021. The future evolution of energy-water-agriculture interconnectivity across the US. Environmental Research Letters. https://doi:10.1088/1748-9326/ac046c
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Binsted, M., Iyer, G., Cui, R., **Khan, Z.,** Dorheim, K. and Clarke, L., 2020. Evaluating long-term model-based scenarios of the energy system. Energy Strategy Reviews, 32, p.100551. https://doi:10.1016/j.esr.2020.100551
Khan, Z., Wise, M., Patel, P., Kim, S.H., Hejazi, M., Burleyson, C., and Iyer, G., 2021. Impacts of long-term temperature change and variability on electricity investments. *Nature Communications*, 12(1), pp.1-12. https://doi.org/10.1038/s41467-021-21785-1

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Relevant Experience

Dr. Tao Zhang's current research focuses on urban heat island and its environmental impacts, including the data source, quantifying methods, drivers, and effects. He is particularly interested in the development of techniques for remote sensing data production and analysis.

Appointments

- 2019-Present, Postdoc Research Associate, Department of Geological and Atmospheric Sciences, Iowa State University

Education

- 2019, Ph.D., Cartography and Geography Information System; University of Chinese Academy of Sciences
- 2014, M.S., Physical Geography; University of Chinese Academy of Sciences
- 2011, B.Eng., Remote Sensing Science and Technology; Wuhan University

Selected Relevant Publications

- Chen, W., Zhou, Y., **Zhang, T.**, et al. Estimating diurnal cycle of land surface temperature by integrating WRF and MODIS LST data. *Remote Sensing of Environment* (To be submitted).
- **Zhang, T.**, Zhou, Y., et al. Urban heat island drives up US building cooling energy consumption, but shows large spatial variations. (in preparation)
- **Zhang, T.**, Zhou, Y., et al. A nearly global coverage dataset of 1km daily land surface temperature (2003-2020). (in preparation)
- **Zhang, T.**, Li, B., Yuan, Y., Gao, X., Jiang, Y., & Liu, Y. (2019). Spatio-temporal Precipitation Dataset in Hengduan Mountains (1998-2012). *Journal of Global Change Data & Discovery*, 2, 168-174.
- **Zhang, T.**, Li, B., Yuan, Y., Gao, X., Sun, Q., Xu, L., & Jiang Y. (2018). Spatial downscaling of TRMM precipitation data considering the impacts of macro-geographical factors and local elevation in the Three-River Headwaters Region. *Remote Sensing of Environment*, 215, 109-127.
- **Zhang, T.**, Li, B., Wang, J., Hu, M., & Xu, L. (2016). Estimation of Areal Mean Rainfall in Remote Areas Using B-SHADE Model. *Advances in Meteorology*, 2016.
- **Zhang, T.**, Li, B., He, Y., Du, J., Niu, H., & Xin, H. (2015). Spatial and temporal distribution of precipitation based on corrected TRMM data in Hengduan Mountains. *Journal of Natural Resources*, 30(2), 260 - 270. (In Chinese)
- **Zhang, T.**, He, Y. Q., Ma, J., & Pang, J. (2014). Spatial and temporal distribution of precipitation based on corrected TRMM data around the Hexi Corridor, China. *Sciences in Cold and Arid Regions*, 6(2), 159-167.

Honors

- 2019, Director Scholarship, Institute of Geographical Sciences and Resources, CAS
- 2012, Merit Student, University of Chinese Academy of Sciences
- 2009, Outstanding Student, National Encouragement Scholarship, Wuhan University