Urban Multi-scale Environmental Predictor - an extensive tool for climate services in urban areas

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Abstract: The city based climate service tool UMEP (Urban Multi-scale Environmental Predictor) is a coupled modelling system that combines models essential for urban climate processes and is developed as an extensive QGIS plugin. An application is presented to illustrate its potential, specifically of the identification of heat waves and cold waves in cities. The tool has broad utility for applications related to outdoor thermal comfort, urban energy consumption, climate change mitigation etc. It includes tools to: enable users to input atmospheric and surface data from multiple sources, prepare meteorological data for use in urban areas, undertake simulations and consider scenarios, and compare and visualize different combinations of climate indicators.

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1. Introduction

Scientists and practitioners from disciplines, such as architecture (e.g. Ren et al. 2011), climatology (e.g. Eliasson 2000), planning (e.g. Alcoforado et al. 2009), engineering and geography, have long been interested in how weather and climate affects cities and city dwellers. However, city based climate services, which require climate knowledge and information, for urban planning, building design and the operation of cities is not straight-forward (Chrysoulakis et al. 2013; Baklanov et al. 2017; Grimmond et al. 2014). Models and tools at the appropriate scales are only now being developed. Input data (e.g. surface and atmospheric) can be challenging to access and/or in formats that are inaccessible to many end-users. Communication between producers and users of climate services has been poor, with outputs that can be difficult to interpret by practitioners and non-specialists. These challenges indicate a need for tools that are more user-friendly, and technically and economically accessible to improve communication across disciplines, researchers and practitioners.

To address this need, we introduce UMEP (Urban Multi-scale Environmental Predictor) an integrated tool for urban climatology and climate-sensitive planning applications. This tool can be used for applications related to outdoor thermal comfort, solar energy production, climate change mitigation etc. UMEP consists of a coupled modelling system which combines different kinds of models with systems to input data from multiple sources, formats and at different temporal and spatial scales, and to generate output as data, graphs and/or maps. An important feature of UMEP is its ability to address issues and relevant processes at the different temporal and spatial scales investigated. Here the structure of UMEP and a practical application to illustrate its potential are presented.

UMEP is being developed as a community tool using only open source software and libraries to enable its use without restriction to users and researchers. Users may contribute to the tool to enhance and extend its capabilities. A major feature is the coupling of climate data with spatial information to determine model parameters, and to edit, map and visualize inputs and results. Therefore, the software is written as a plug-in to QGIS, a cross-platform, free and open source desktop geographic information system (GIS) application (Team 2016).

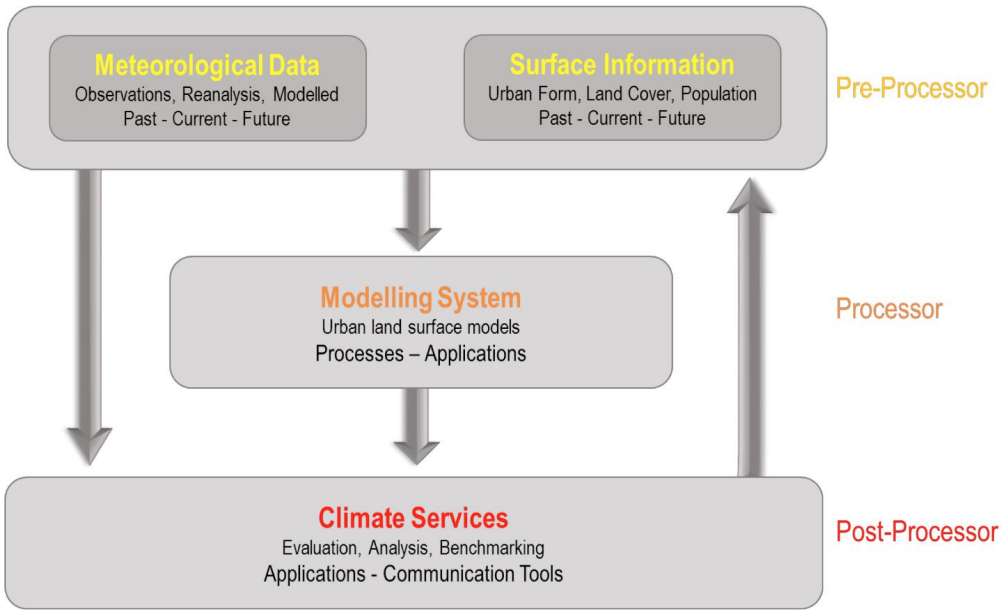

Figure 1: Structure of UMEP (Urban Multi-scale Environmental Predictor).

UMEP has three main elements (Figure 1): pre-processor (for inputs of meteorological and surface information); processor (modelling system e.g. Urban Land Surface Models, ULSM); and post-processor (tools to analyze the outputs (individual and ensemble, indicators of uncertainty, user applications etc.). Each separate tool (plug-in) is described briefly in Table 1, with full details presented in the online manual (www.urban-climate.net/ umep/UMEP). UMEP allows users to: integrate atmospheric and surface data from multiple sources; take data measured at 'standard' sites and adapt it to be representative location within the urban environment; and compare and visualize results or scenarios for different climate indicators of concern or interest (heat indices, intense precipitation, water/energy demand) at a range of spatial scales consistent with end-users' needs and interests. For ease of use, tutorials have been developed (http://www.urban-climate.net/umep/UMEP_Manual Tutorials) for users to try out the different parts of the tool. A key contribution of UMEP is to facilitate the preparation of input data needed for City-Based Climate Services (CBCS). UMEP provides both guidance and tools that enable the preparation and manipulation of data. These tools can be found in the pre-processor section (Table 1). This is particularly important as most end-users are familiar with some, but not the full spectrum of data needed for applications. For example, planners are knowledgeable about buildings heights, materials and their spatial arrangement (i.e. urban surface data) and often have geographic information system (GIS) skills, but they do not necessarily have detailed knowledge of meteorological data.

2. Structure and Capabilities of UMEP

UMEP broad range of capabilities includes tools that may be used independently and/or in combinations depending on the application. The output from pre-processor tools may be used for other external modelling applications, or within a chain of tools to provide climate indicators for decision making. Many of the individual tools, and their evaluation, have been described in numerous previous papers; see Lindberg et al. 2017 for details.

3. Application Example - Energy and Water Balance Fluxes

Energy and water balance fluxes are critical to surface-atmosphere interactions in an urban area. The Surface Urban Energy and Water balance Scheme (SUEWS) is a core urban land-surface model included in the processing part of UMEP (Table 1). The model is able to simulate the urban radiation, energy and water balances using commonly measured meteorological variables and information about the surface cover. SUEWS is applicable at the local (neighborhood) to city scale. UMEP has the latest version of SUEWS (Ward and Grimmond 2017, Ward et al. 2016) accessible through two links:

(a) SUEWS Simple: is intended to provide a useful starting place to introduce UMEP and SUEWS. Example data are provided so that the user can explore the impact of modifying urban surface characteristics. With SUEWS Simple, the ULSM can be executed for a single location (area).

(b) SUEWS (Advanced) provides a full version of the model appropriate for both spatial and temporal investigation of the urban energy balance.

The SUEWS model has been extensively evaluated at various locations and situations worldwide (see Lindberg et al. 2017).

Component	Scales	Description
Pre-Processor		
Prepare existing data	C/L/M	Formats meteorological data for input to the models, dealing with missing data
Download data (WATCH)	C/L	Re-analysis data modified for use in an urban context, representative of the local scale
Spatial Data Downloader	C/L/M	Downloads spatial data from public servers
Tree Generator	C/L/M	Creation/manipulation of 3D vegetation data
LCZ Converter	C/L	Allows morphometric parameters and land cover fractions to be calculated from Local Climate Zone (LCZ) maps.
Sky View Factor	L/M	Amount of the hemisphere with restricted view of the sky
Wall Height Aspect	L/M	Height and orientation of buildings and walls
Land cover reclassifier	C/L/M	Geodata can be translated into the land cover classes used by all the models
Land cover fraction (point)	L/M	Surface cover fractions are determined for an area or specific directions
Land cover fraction (grid)	C/L	As above, but a grid is used to determine fractions for multiple areas.
Morphometric Calculator (point)	L/M	Morphometric parameters are determined for an area or specific directions can be used.
Morphometric Calculator (grid)	C/L	As above, but a grid is used to determine parameters for multiple areas.
Source area (point)	L/M	As above, but determined for an area derived from source area models.
SUEWS Prepare	C/L	Prepares input data for the SUEWS model (processor).
Processor		
ExtremeFinder	C	Heat and cold wave conditions.
Mean Radiant Temperature (SOLWEIG)	L/M	SOLWEIG estimates spatial (2-D) variations of 3-D radiation fluxes and the mean radiant temperature (T_{mrt}) in complex urban settings.
Anthropogenic Heat (LQF)	C/L	Globally applicable method (low spatial resolution) to calculate Q_F
Anthropogenic Heat (GQF)	C/L	Locally applicable method (high spatial resolution) to calculate Q_F
Urban Energy and Water Balance (*SUEWS; Simple*)	C/L	Urban land surface model of radiation, energy and water fluxes for a single point or area.
Urban Energy and Water Balance (*SUEWS; Advanced*)	C/L	As above, but for multiple areas.
Solar Energy on Building Envelopes	L/M	Shortwave irradiance on ground, roofs and building walls.
Daily Shadow Patterns	L/M	Shadow maps are derived from buildings and 3D vegetation.
Post-Processor		
SEBE (Visualization)	L/M	Visualization of solar irradiation on building envelopes i.e., both roofs and walls.
SOLWEIG Analyzer	L/M	Analyzing output from the SOLWEIG model.
SUEWS Analyzer	C/L	Analyzing output from the SUEWS model.
Benchmarking	C/L/M	Statistical tool to compare different datasets

Table 1: Description of UMEP components and scales applicable to: C: city; L: local (neighborhood); M: micro (e.g. street canyon, park). Micro scale applications can be used across a whole city, but will likely be computer intensive.

3.1. Energy and water balance fluxes for Beijing, China

In this example the implication of a heat wave event compared to a 'normal' summer month is compared with regards to sensible heat flux over Beijing, China. The workflow for this application is outlined in Figure 2. Geo-datasets that contain information about the urban environment are used with the pre-processor tools to provide the required surface parameters. It is strongly recommended that all geodata used are transformed into the same projected coordinate system. The model can be applied to areas of any shape, here referred to as 'grids'. These areas need to be defined in a vector polygon layer. In most cities, there will be planning units with known boundaries already available in this format (e.g. boroughs, wards). In this example a square grid is created in QGIS, e.g. by using Vector >Research Tools >Vector grid.

As land cover information is a key characteristic for many calculations, a method to reclassify data is provided (Land Cover Reclassifier). In this application example, no specific spatial input data exists and thus other sources of information is required. Accessing reliable sources of land cover information to derive these parameters at the scale of interest remains a challenge. Crowd-sourced data sets such as OpenStreetMap (http://www.openstreetmap.org) and WUDAPT (http://www.wudapt.org/) offer potential but may be incomplete or inconsistent. In this example, Local Climate Zones (Stewart and Oke 2012) is derived using the LCZ converter available from the UMEP pre-processor. This tool converts WUDAPT data into input information for SUEWS (Figure 3).

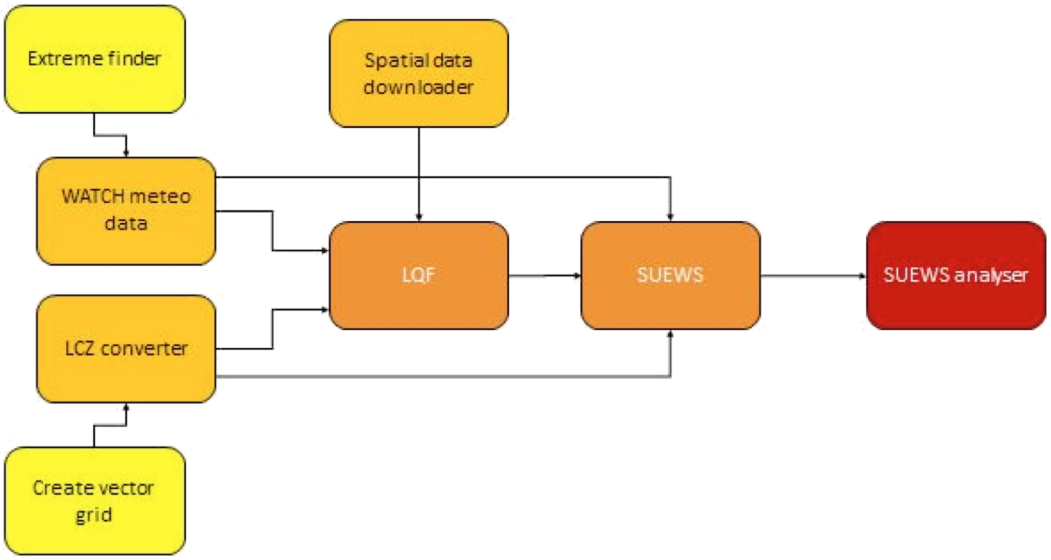

Figure 2: Workflow of an urban energy and water balance application.

Morphometric parameters required as model input can be calculated using the Morphometric Calculator (Grid) using digital surface models (DSM). From these data, the zero-plane displacement height (zd), aerodynamic roughness length (z0) and other geometric parameters such as mean roughness-element height and frontal area index can be calculated. In this application example this information is parameterized from the WUDAPT LCZs. However, if more detailed information is available, this can be utilized.

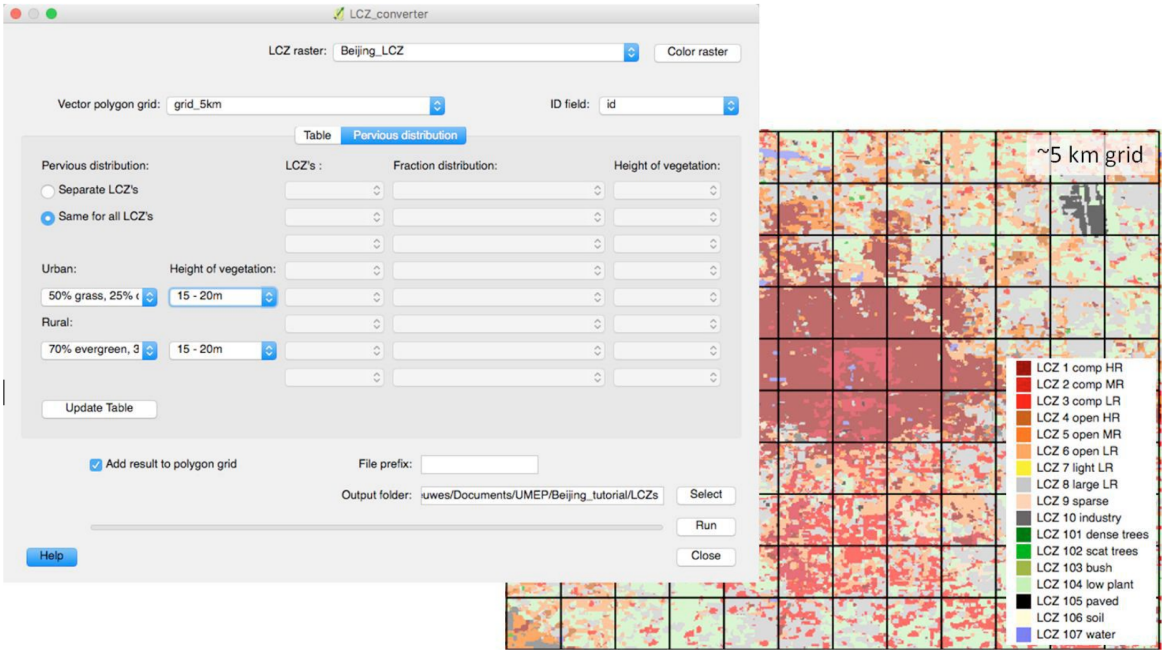

Figure 3: (left) LCZ Converter interface in UMEP and (right) Beijing LCZs derived from the WUDAPT database (www.wudapt.org).

Population density (people per hectare) is used in the estimation of anthropogenic heat flux in SUEWS. In this example population density datasets are unavailable (e.g. as would be obtained from local census data), so the Spatial Data Downloader can be used. This plug-in is directly connected to various Web Coverage Services (WCS) including global datasets on population density. Population information has to be (dis-)aggregated based on the polygon grid. This is preferably done using the built-in tool Zonal statistics in QGIS.

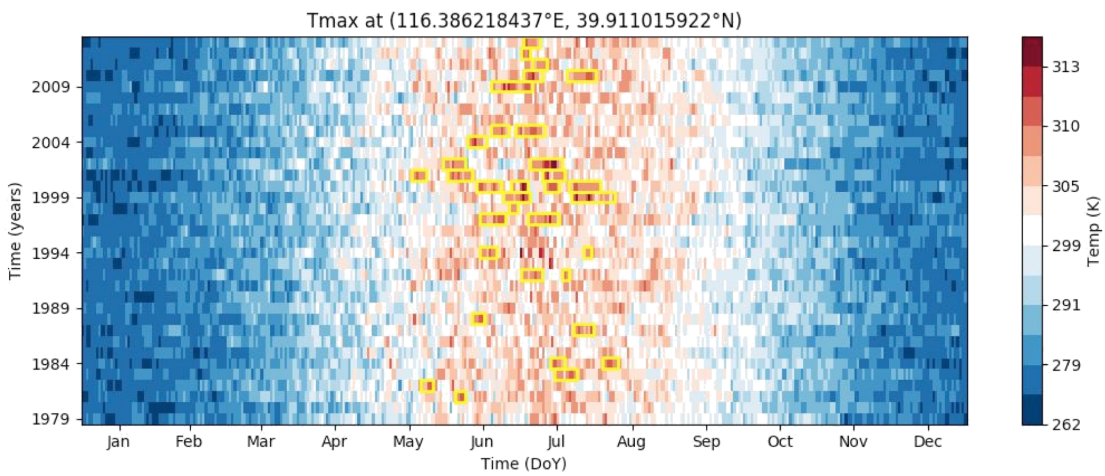

Figure 4: Output from the ExtremeFinder where yellow boxes are identified as heat wave periods.

The other major input is the forcing meteorological data. This needs to be for above the height of the roughness elements (trees, buildings). A common format is used in all UMEP models but unnecessary data for a specific application does not need to be supplied. Most applications require a continuous gap-filled data set. For many urban applications, the impact of daylight savings starting and finishing is important. In this example, the ExtremeFinder is

used to identify years with 'normal' and 'heat wave' summer situations for Beijing (Figure 4). In this example 2006 was identified as a 'normal' and 2009 as a 'heat wave' summer. When the years of interest have been identified, the WATCH data plugin in UMEP is used to retrieve data from the years of interest. UMEP allows the user to draw on the reanalysis dataset, WATCH Forcing Data ERA-Interim (WFDEI) (Weedon et al. 2011). This product was selected as it was designed to be used for hydrological and land-surface modelling for climate purposes. It is derived from the ERA-Interim reanalysis product (Dee et al. 2011) via sequential interpolation to half-degree spatial resolution with 3 h temporal resolution (Weedon et al. 2011, Weedon et al. 2014).

Once all the required information has been pre-processed, the SUEWS model can be executed through the UMEP processor. Results from two example model runs are shown in Figure 5 where the increase in sensible heat (QH) is evident. The two maps are generated using the SUEWS Analyzer in the post-processor section in UMEP. This enables simple exploration of spatial and temporal model results.

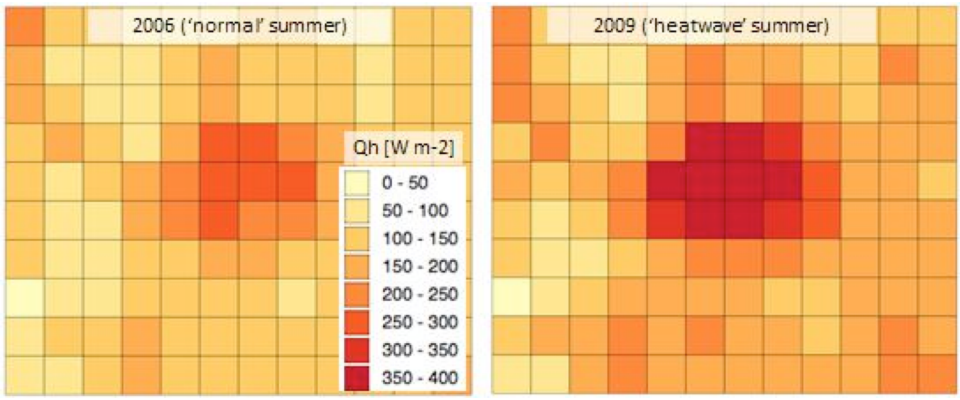

Figure 5: Mean sensible heat flux at 13:00 local time during July for Beijing, China.

4. Summary and Future Prospects

This paper introduces the Urban Multi-scale Environmental Predictor, UMEP and gives an example its potential through an application. Designed as a plug-in for QGIS, UMEP consists of a coupled modelling system which combines state of the art 1-D and 2-D models related to processes essential for urban climate estimation. The tool has broad utility for applications related to outdoor thermal comfort, urban energy consumption, climate change mitigation etc. The grid-based source area estimations of morphometric parameters such as z0 and zd (Kent et al. 2017) allows interpretation of observations and preparation of data for climate modelling. Planned developments include tools for pedestrian wind and thermal comfort indices; generation of site-specific forcing data using a coupled convective boundary layer (CBL) and land surface model (Onomura et al. 2015).

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