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Integration of remote sensing based surface information into a three-dimensional microclimate model

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ABSTRACT

Climate change urges cities to consider the urban climate as part of sustainable planning. Urban microclimate models can provide knowledge on the climate at building block level. However, very detailed information on the area of interest is required. Most microclimate studies therefore make use of assumptions and generalizations to describe the model area. Remote sensing data with area wide coverage provides a means to derive many parameters at the detailed spatial and thematic scale required by urban climate models. This study shows how microclimate simulations for a series of real world urban areas can be supported by using remote sensing data. In an automated process, surface materials, albedo, LAI/LAD and object height have been derived and integrated into the urban microclimate model ENVI-met. Multiple microclimate simulations have been carried out both with the dynamic remote sensing based input data as well as with manual and static input data to analyze the impact of the RS-based surface information and the suitability of the applied data and techniques. A valuable support of the integration of the remote sensing based input data for ENVI-met is the use of an automated processing chain. This saves tedious manual editing and allows for fast and area wide generation of simulation areas. The analysis of the different modes shows the importance of high quality height data, detailed surface material information and albedo.

1. Introduction

In built up areas, the climate differs from the rural climate as a result of the urban fabric, the urban structure and human activities. Characteristic aspects of the urban climate are the urban heat island and lower air quality (e.g. because of smog), among others (Landsberg, 1981). Urban climate is commonly studied at local scale (1–50 km) or microscale (10 m–10 km) (Oke, 1987). Urban heat islands, for example, are often studied at a local scale. At a microscale microclimatic effects between several buildings (e.g. a street canyon) are studied, such as small scale turbulence around buildings (Oke, 1987).

Because of the impact of climate change on urban areas, it is important that cities develop adaptation and mitigation strategies for sustainable development (Carter et al., 2015). Therefore, it is important for urban areas to gain knowledge on the microclimate. It is well known that the microclimate is influenced by the design of the urban surface and the urban structure (Oke, 1988; Arnfield, 2003). However, surface based microclimate modelling is challenging, because of the high complexity of the models and the large amount of specific input parameters that are required to run these models (Chen et al., 2012). Currently, several microclimate models are available that are able to handle the complexity of the urban environment, for example MUKLIMO_3 (Sievers and Früh, 2012), TUF-3D (Krayenhoff and Voogt, 2007) and ENVI-met (Bruse and Fleer, 1998). They enable simulations of the microclimate around a single building, in a street canyon or even several building blocks. However, because of the numerous input parameters required they are often used to simulate synthetic landscapes assuming standardized building forms, materials and vegetation types (Shashua-Bar et al., 2004; Taleghani et al., 2015) and they are not very common in urban planning practice. Although studying the effect of certain spatial characteristics on the microclimate using synthetic landscapes can be very useful, the simulation of real world urban landscapes is very desirable for urban planning purposes (Ching et al., 2009).

For large scale and non-urban meteorological models, remote sensing provides a common source of input data. Regional models such as COSMO-CLM use several remote sensing based data sets

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such as land cover (e.g. GlobalLand2000) and LAI (e.g. MODIS) (Smiatek et al., 2016). To ensure that satellite data products at global scale are suitable for climate modelling and analysis, requirements are formulated by the Global Climate Observing System (GCOS). These requirements are followed by large satellite data programs that aim at climate applications (e.g. NOAA in USA (https://www.ncdc.noaa.gov/cdr), EUMETSAT (Schulz et al., 2009) and ESA CCI (Hollmann et al., 2013) in Europe). In the urban context, remote sensing data are commonly used to study the urban climate at meso and macro scales. Remote sensing products such as biophysical parameters (e.g. vegetation fraction), land cover or albedo are used to parameterize climate models at the scale of provinces, countries and continents (Yang, 2000; de Foy et al., 2006; Jin et al., 2007). In addition to optical satellite data, thermal infrared (TIR) remote sensing data are also commonly used for urban climate studies (Weng, 2009). The land surface temperature (LST) derived from this data is an important input parameter for (urban) surface heat flux models and radiation models (e.g. Kato and Yamaguchi, 2007; Weng et al., 2014; Chrysoulakis et al., 2015). The urban heat island, which can be studied with TIR data as well, is a frequently studied aspect of the urban climate. Often its relationship to land cover characteristics such as impervious surface or vegetation is studied (Weng et al., 2004; Jenerette et al., 2007; Yuan and Bauer, 2007; Maimaitiyiming et al., 2014). At local scale, surface albedo and urban structure have been studied and mapped to support the modelling of urban energy fluxes or surface temperature patterns (Hoyano et al., 1999; Frey et al., 2007; Wu et al., 2013). Especially at local scales, the urban structure cannot be described without information on the third dimension. Therefore digital elevation models (DEM) are used. Many DEMs are derived from remote sensing data, e.g. using LIDAR data or stereo imagery and are commonly used in urban microclimate models (e.g. Yu et al., 2009; Lindberg and Grimmond, 2011).

Other studies focus on categorization of urban areas into local climate zones (Stewart and Oke, 2012). LCZs are separated based on surface characteristics (e.g. land cover, imperviousness, vegetation) which can be very well distinguished by remote sensing (Ching et al., 2009; Bechtel and Daneke, 2012; Bechtel et al., 2015; Leconte et al., 2015). LCZs are especially developed for use in climate studies, but they show large similarity to urban structure types (USTs) which are used by urban planners, e.g. in Germany (Pauleit and Duhme, 2000; Heiden et al., 2012).

Still, remote sensing products have rarely been implemented into urban microclimate models. One of the main reasons is that microclimate models are often designed to calculate idealized scenarios representing a real-world setup and therefore often lack an interface for the direct use of remote sensing data or products. The lack of suitable detailed remote sensing products about urban surface characteristics and appropriate concepts to integrate surface information into urban microclimate models is another reason for the limited use of remote sensing products for microclimate modelling. In fact, microclimate models require information on the physical properties of urban objects like reflection, absorption, emissivity, specific heat capacity but also their height and spatial arrangement. As an example, the ENVI-met microclimate model (Bruse and Fleer, 1998) considers the interaction between vegetation, atmosphere, and urban surfaces and allows the study of multiple aspects of the urban microclimate. Table 1 shows the large number of input parameters required by ENVI-met. In scenario studies of a synthetic area this is not a problem, but when the objective is to simulate a real existing neighborhood, gathering the input data in the field is a tedious job, because of the many different materials of the often small urban objects. Often, this is solved by using the real location of the buildings, e.g. from a cadaster data set, but reducing the number of other objects and assuming only a limited number of most common materials for the study area (e.g. Toparlar et al., 2015). However, if the materials in the area vary a lot, which is the case in most cities (Small, 2001; Herold et al., 2003), it is desirable to use an automated approach to integrate the full variety of surface characteristics into the microclimate model.

One of the few studies that did use remote sensing for microclimate modelling, by Xu et al. (2008), have derived land cover, surface temperature, albedo, vegetation fraction and emissivity parameters from airborne Operative Modular Imaging Spectrometer data (OMIS) to model urban heat flux based on the relatively simple LUMPS (Grimmond and Oke, 2002) and ARM (Voogt and Grimmond, 2000) schemes. Using these airborne hyperspectral data, five broad land cover classes have been identified supported by aerial photography and a survey map as input data. The modelled sensible heat-flux values showed good agreement but the study also emphasizes the need of large spectral and spatial coverage together with high spatial and spectral resolutions to derive surface characteristics on a high thematic detail. Similarly, He et al. (2015) use airborne hyperspectral data to estimate net shortwave radiation and Liu et al. (2016) use hyperspectral airborne data in the reflective and thermal wavelengths to model land surface temperature. Various studies aiming at automatic differentiation of urban surface materials have shown the high potential of hyperspectral remote sensing (Herold et al., 2004; Heiden et al., 2007; Cavalli et al., 2008; Roessner et al., 2011; Okujeni et al., 2013). Since detailed surface characteristics preferably at material level are required at high spatial resolution, airborne hyperspectral data is a suitable data source matching the requirements of microclimate studies. Further, urban structure information is important information that can be derived from DEMs.

The overall aim of this study is to explore how microclimate analysis of urban areas can be supported by automatically generated surface information using high resolution airborne hyperspectral data and height data derived from stereo imagery. This information includes the location and material of objects and surfaces, as well as several properties thereof (albedo, leaf area index, height). The objectives of this study are (1) to generate detailed urban surface information from airborne hyperspectral and height data from stereo imagery and integrate it into the ENVI-met microclimate model, (2) to show the plausibility of the RS based input data by comparing simulation results using automated RS based and manually prepared input data and (3) to demonstrate and discuss the impact of RS-based surface material information on the simulation results and thus, the importance of data and techniques able to derive such information. The results of the study of Heiden et al. (2012) form the data base of the spatially continuous and detailed urban surface information comprising material and structural parameters for this study. Heiden et al. (2012) and van der Linden and Hostert (2009) have discussed the advantages and limitations of surface characterization of urban objects using airborne hyperspectral and height data in detail. Therefore this study focuses on the integration of the surface characteristics rather than their generation.

2. Methods

In this highly interdisciplinary study remote sensing products are integrated into a microclimate modelling environment. The main challenge is to bring both domains together and show that this approach produces meaningful results. Therefore, the method section is divided into the description of the principles and functionality of the ENVI-met microclimate model (Section 2.1) clarifying the requirements for study area setting and RS data integration (Section 2.2), the RS input data specification and pre-processing to understand the origin and quality of the data (Section 2.3), the