ABSTRACT

The urban micro climate is important for the well-being of citizens. With simulation models the urban micro climate can be studied and recommendations can be made to improve the micro climatic situation. However, mainly synthetic scenarios are simulated due to a lack of information. The objective of this paper is to explore the potential of airborne hyperspectral and height data to provide area wide information for micro climate simulations, by the example of the model ENVI-met. First the requirements for such a model are presented. Then an approach is presented in which a surface material map, surface albedo and leaf area index are derived from hyperspectral HyMap data and the object height from HRSC height data. These products are implemented as input parameters for the urban micro climate model. The paper shows that based on hyperspectral and height data realistic urban micro climate simulations can be carried out.

1. INTRODUCTION

The urban micro climate strongly influences the wellbeing of inhabitants of cities [1]. Therefore urban planners need to address the urban micro climate in their spatial plans. To do so, urban planners need area wide information on the urban micro climate. Currently, micro climate analysis is carried out mainly based on point measurements (e.g. weather stations, measurements of pollutants) or simulation models. Simulation models have the potential to provide an area wide analysis of the micro climate in parts of the city. However, mainly synthetic scenarios are studied with micro climate models, because information on the actual situation of an area is often difficult to obtain. Spatial characteristics influence the urban micro climate and information about them is required to simulate the urban micro climate for a realistic environment [2]. Examples are the location and materials of buildings and the location and type of vegetation influence. Often, this information can only be obtained by extensive field surveys. Remote sensing is a suitable tool to derive area wide spatial information, reducing the need for field surveys. For urban applications a high spatial resolution of the sensor is preferred to separate the relatively small urban objects [3]. The high spectral resolution provides the potential to identify a large range of surface materials [4]. This makes hyperspectral remote sensing a very promising tool for this application.

The objective of this paper is to explore the potential of hyperspectral remote sensing to support micro climate simulations. Firstly, an inventory of the data requirements for micro climate simulations is made. The micro climate model ENVI-met [5] is selected as exemplary micro climate simulation model. This 3D model simulates the interaction between urban surface, vegetation and atmosphere. In contrast to other published urban micro climate models, ENVI-met simulates multiple climatic aspects simultaneously and is available for free at www.envi-met.com. Secondly, an approach is presented how these input parameters can be derived with hyperspectral and height data obtained by remote sensing systems and how the corresponding data can be used to support simulations of the urban micro climate with the ENVI-met software.

2. DATA REQUIREMENTS FOR URBAN MICRO CLIMATE MODELLING

The urban climate differs from the climate in rural areas in temperature, precipitation and air quality, amongst others. A well-known regional phenomena resulting from the different climate in built up areas is the urban heat island. At a local scale (< 2 km) the urban micro climate is studied [1]. At this scale buildings and human activities influence the main climatic parameters temperature, humidity and precipitation, wind and air quality. It is an important scale, because changes in temperature, humidity, wind, and other climate parameters can be sensed directly by the citizens and they influence their well-being [6].

The micro climate is a complex system and its modelling usually starts with the energy balance [7]. This balance includes the incoming and outgoing shortwave and long-wave radiation, anthropogenic heat, heat storage in buildings and surfaces, evapotranspiration, and heat advection by wind [8]. The urban energy balance directly determines surface and air temperature and also influences wind and humidity. Urban objects and activities influence the energy balance by their capacity to store or reflect radiation, their potential for evapotranspiration or their influence on the wind flow, among others. Knowledge about the influence of urban characteristics on the energy balance is important for urban planning. Clever use of this knowledge enables to mitigate negative influences on the micro climate and
can increase the climatic comfort of the inhabitants, e.g. by creating fresh air corridors to reduce heat in summer (Kuttler1998). Because their importance the influences of urban characteristics are a popular research topic. For example, relations between surface cover, land use, percentage impervious surface, vegetation density and urban structure and climate parameters such as air and surface temperature, humidity and heat flux have been studied, for example in [9,10,11,12,13]. These spatial aspects have to be taken into account when modelling the urban micro climate. In addition, information on the regional and global climate and weather circumstances (temperature, irradiation, wind speed and direction) are required.

For the simulation of the urban micro climate the micro climate model ENVI-met requires a spatial description of the test area and four (standard) databases containing thermal and hydrological properties of the materials and surfaces present in the area. In the file describing the spatial configuration of the test area the location, height, wall material and roof material are stored. Additionally, the location, type and height of vegetation (trees, lawn) have to be provided, as is the surface material and soil type of non-built surfaces. For a detailed overview of the ENVI-met model and its input parameters, the reader is referred to www.envi-met.com.

Table 1: Input parameters and their sources required for urban micro climate modeling with ENVI-met

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Roof material</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Height</td>
<td>Stereo imagery</td>
</tr>
<tr>
<td>Material properties: reflectance properties</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Material properties: thermal inertia</td>
<td>Literature</td>
</tr>
<tr>
<td>Vegetation</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Type (deciduous, coniferous, grass)</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Height</td>
<td>Stereo imagery</td>
</tr>
<tr>
<td>Leaf area density</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Photosynthetic and evapotranspiration properties</td>
<td>Literature</td>
</tr>
<tr>
<td>Non-build surfaces</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Type (impervious, pervious)</td>
<td>HyMap data</td>
</tr>
<tr>
<td>Soil properties (hydrological)</td>
<td>Literature</td>
</tr>
<tr>
<td>Weather conditions</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Weather station or simulation variable</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Weather station or simulation variable</td>
</tr>
<tr>
<td>Date, sun dawn, sun set</td>
<td>Depending on location</td>
</tr>
</tbody>
</table>

In tab. 1 the main input parameters required by ENVI-met are listed. For each parameter the potential source is indicated. The spatial input parameters can be retrieved very well with remote sensing, saving time for collecting this information in the field. To reach the scale of the micro climate model (ENVI-met uses typical grid cells of 2 – 10 m), remote sensing data with a high spatial resolution is required. In addition, the spectral resolution should be high enough to enable the separation of surface materials. Airborne hyperspectral remote sensing can provide both the required spatial and spectral resolution. To provide the ENVI-met model with information on the height of buildings and vegetation, height data is required, e.g. derived from stereo aerial photographs.

A detailed surface material map derived from airborne hyperspectral data can provide most of the spatial parameters regarding location, type and material of urban objects. Additionally, it enables the assignment of material related thermal properties to spatial locations. The hyperspectral data can also provide surface albedo to provide the model with information on reflectance properties of the surfaces. The leaf area density of vegetation describes the area of leaves at a certain height of the vegetation and is directly related to the leaf area index (LAI). LAI is a common remote sensing product and can also be derived from the hyperspectral data. Object height information derived from stereo sensing cover the last spatial characteristics required by ENVI-met. Additionally, ENVI-met requires information about the thermal and hydrological properties of surface materials and soils. For this exploratory study, default values provided by ENVI-met software and literature [7, 14] are used. Input parameters regarding the weather and climate situation can be derived from a weather station near by or used as variable to simulate different weather scenarios.

3. DATA AND METHODS

Based on the analysis of the required input parameters for the ENVI-met model described in the previous section, airborne hyperspectral data and height data derived from stereo imagery are used to derive the following products. A surface material map, surface albedo and leaf area index (LAI) are derived from hyperspectral data from the airborne sensor HyMap [15]. Object height of buildings and vegetation is derived from stereo imagery from the HRSC camera [16]. A study area in the centre of the German city of Munich is selected to test the approach. The HyMap data is recorded on 17 and 25 June 2007 with a spatial resolution of 4 m and 125 spectral bands covering a spectral range from 450 to 2500 nm. Before use the HyMap data was atmospherically corrected with
ATCOR software [17] and geometrically corrected with ORTHO [18]. The HRSC height data was recorded in September 2004 and received as a digital elevation model (DEM) containing both the height of the terrain and the objects. The height data was resampled to 4 meter to match the HyMap data. Extra effort was put on the co-registration of the HRSC and HyMap data sets by using additional ground control points, reaching a co-registration accuracy of 0.8 pixels RMSE in average.

The surface material map is derived from the HyMap data using a linear spectral unmixing algorithm developed especially for urban applications by the GFZ German Research Centre for Geosciences [19, 20]. With this unmixing approach around 30 urban surface materials can be identified at sub-pixel level. They include various roof materials, materials of impervious, partially pervious and pervious non-built surfaces and three vegetation types (grass, coniferous and deciduous trees). The semi-automatic algorithm consists of three steps. The first step is the automatic identification of pure pixels to retrieve endmember spectra. The second step is the identification of pure pixels (called seedlings) based on the selected endmembers and the third step is the actual unmixing. The unmixing starts with the mixed pixels next to the seedling pixels and addresses the whole image in several iterations. Mixture models of two endmembers are tested and the combination with the lowest RMSE is selected. For the selection of mixture models for testing the surface materials that have been assigned to neighbouring pixels and a priori information on the presence of buildings (e.g. from height or cadastre data) are taken into account. The result is an abundance map per pixel for each surface material.

The surface albedo is derived from the HyMap data by calculating the average reflectance over all wavelengths for each pixel. Hereby the definition provided in [21] is followed. The albedo map provides average numbers of surface albedo for surface materials and enables also to adjust the albedo of the surface in single pixel.

The leaf area index is calculated from the HyMap data using the normalised vegetation index (NDVI) according to the MODIS backup algorithm [22]. Within this algorithm a look-up table with LAI values according to a certain NDVI value is used to determine the LAI in pure vegetation pixels. Subsequently the leaf area density (LAD) is calculated trees according to the equations provided by [23].

The object height is derived from the HRSC-DEM by subtracting a digital terrain model (DTM) from the SRTM database [24]. The accuracy of the resulting object height was validated for 200 buildings and was found to be +/- 2 meter. All objects higher then 4 meter are considered buildings or trees.

Finally, the derived remote sensing products are automatically integrated in ENVI-met files using algorithms written for this purpose in IDL. With these files micro climate simulations are carried out for a subset of 400 x 400 m (see fig. 1), simulating 24 hours on a day in June in Munich. Each hour, the state of the climate parameters (humidity, wind speed and direction among others) is saved. The subset includes four building blocks with regular block developments and two blocks with dense block developments and in the middle of the subset is a small park.

4. RESULTS

Fig. 2 shows the results of the remote sensing products for the subset. Figure 2a shows the material map. To make the interpretation easier, only the material with the largest abundance is displayed for each pixel. The linear spectral unmixing could be carried out with an RMSE of less then 2 % reflectance. The abundances were accurately estimated with a mean absolute error of 2.2 % at building block level. The dominant roof material in the test area is roofing tiles, on the larger buildings in the north and south of the subset also metal is applied. Most of the non-built spaces are covered with vegetation. Several asphalt and cobble stone streets can be recognised. Other streets, however, were obscured from the sensor field of view by the crowns of the trees aligning the road and could not be identified as such.

In fig. 2b the albedo image is shown. The albedo of the buildings is clearly higher than that of the vegetation. Among the buildings the variation is mainly caused by different orientation of the building roofs towards the sun and different materials. For example the flat large
building with a concrete roof has a lower albedo than the large building structure with roofing tiles in the north of the subset.

Fig. 2c shows the LAI for all vegetated areas. The LAI is for most of the vegetation quite high (> 5). Only along the edges of the vegetation lower LAI values are found. The LAI values of trees are used to calculate the leaf area density.

Finally, fig. 2d presents the object height as derived from the HRSC data after DEM-normalisation. The square structures of the buildings and the more fuzzy structures of the vegetation can clearly be recognised.

Fig. 3 shows how these four remote sensing products are subsequently used to prepare the input parameters for the micro climate model ENVI-met. This model requires four layers for the description of the spatial parameters: one for vegetation, for soil, for building material and for wall/building height. In the ENVI-met software they are combined and a 3D simulation environment is created (fig. 3f). This figure shows that the subset can be represented realistically using the hyperspectral and height data as input parameters. Solely streets aligned with trees cannot be represented that well because the tree crowns are blocking the view on the street. In this case too little impervious surface is provided to the model.

The calculated surface albedo is included into a database describing roof material properties. Similarly, also the leaf area density, calculated from the LAI, is included in a database describing the vegetation properties. Here also the height of the vegetation is indicated.

With the generated input data a simulation of the micro climate during 24 hours is carried out with ENVI-met. In the fig. 4 the situation at 15:00 displayed for four variables: air temperature, wind speed and direction and humidity. In the simulated scenario the wind came from the south-west. Fig. 4 shows that the wind influences the air temperature. In the building block marked with a the wind speed is almost zero. The temperature lays around 292.3 Kelvin (19.15 °C) in this building block. At the sun-exposed sides of the buildings the air temperature is higher: around 292.8 Kelvin. It should be noted that the temperature variation within the area is all within 3 degrees. Fig. 5 shows the simulated humidity in a transect of the subset. Between the buildings the humidity is around 5 % lower than in the park in the centre of the transect.

For urban planning purposes indices for the human comfort are very helpful. Such indices provide information on the well being of humans, e.g. if a
location is too hot or too cold for them. The micro climate model ENVI-met calculates several human comfort indicators for the simulated micro climate situation in the model area. The predicted mean vote (PMV) is one of them. Originally developed for the assessment of indoor climate by [25] the index has been adapted for assessment of the outdoor climate [26]. The index is based on micro climate characteristics and physiological, clothing and movement characteristics of a person. The values range from -3 (a person would feel uncomfortably cold) to 0 (comfortable climate situation) to 3 (a person would feel uncomfortably hot). Fig. 6 shows the PMV calculated by ENVI-met based on the simulated micro climate at 15:00. It shows that there are no very uncomfortable locations in the study area at this time of the day. However, on the west and south sides of the buildings, a person would feel slightly warm (PMV around 1.7). On the other hand, at the east (and thus shaded) sides of the buildings a person would feel slightly cold (PMV around -1).

5. DISCUSSION

The assessment of the data requirements of urban micro climate models in general and the ENVI-met model in particular (summarized in table 1) showed that many requirements concern with spatial information. Therefore an approach was developed and tested to derive the required information from hyperspectral HyMap data of Munich. Height data were additionally required to derive the height of buildings and vegetation, which is important to simulate the wind flow amongst others. With linear spectral unmixing a large range of surface materials could be mapped at sub-pixel level, which can be considered a key product to describe the test area for the ENVI-met model. Building and vegetation structures and most streets could be accurately identified. However, some streets are excluded because they are overshadowed by tree crowns. This is a well known problem in urban remote sensing, for example discussed by [27]. Using additional images recorded in winter could provide a solution.

Surface albedo and leaf area density calculated from the LAI are two additional products that the hyperspectral data was to provide. With this more than half of the parameters required by the ENVI-met model can be derived with remote sensing. It could be shown that the derived remote sensing products could be successfully implemented and used for simulations with the ENVI-met model. The simulation results of temperature, wind, humidity and predicted mean vote shown in this paper showed that the micro climatic situation could be modelled realistically. The detailed description of the study area enabled by the hyperspectral data allowed a differentiation of the micro climate, especially between building blocks and parks. Because the input files for the ENVI-met model can be created with few interactive...
steps, a lot of time can be saved both in field surveys and manually entering the required spatial data into the ENVI-met model. Although the hyperspectral products allow the simulation of micro climatic variations within a few building blocks an extensive validation and sensitivity analysis of the ENVI-met model regarding the remote sensing products is required to evaluate which products should be improved to reach more accurate simulation results.

6. CONCLUSIONS AND OUTLOOK

From the presented approach and results it can be concluded that airborne hyperspectral remote sensing has a high potential to support urban micro climate analysis by providing a wide range of spatially detailed input parameters for an urban micro climate model which was shown by the example of the urban micro climate model ENVI-met. The modelling and simulation of the micro climate in existing urban areas instead of synthetic situations can support urban planners to improve the micro climatic situation, e.g. by providing insight in human comfort aspects by indices such as the PMV.

In future research the application of micro climate modelling for larger areas, e.g. a neighbourhood or small town will be investigated, as well as the potential of the presented approach for urban planning purposes. Further an analysis of the sensitivity of the ENVI-met model to the accuracy of the remote sensing products will be of interest. For the study presented in this paper only hyperspectral data in the optical part of the spectrum was available. However, an analysis of the potential of thermal (hyperspectral) data would be of great interest. Not only is an improvement of the material identification to be expected of such data, but also additional input parameters relevant for micro climate modelling are expected to be retrieved, such as emissivity and heat storage capacity.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Segl for providing the unmixing algorithm, Prof. Bruse and S. Huttner for providing a beta version of ENVI-met 4 and their support for the use of the model, DLR Berlin for providing the HRSC data and the German Federal Ministry of Education and Research (BMBF) for their financial support in the context of the project “Refina - Flächenbarometer” (0330737A).

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