# Climate Change in Cities – Can Remote Sensing Help to Optimise Mitigation Strategies?

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## 1 ABSTRACT

Urban planners become more aware that climate change is likely to have influence on the liveability in cities. Therefore, the number of planning authorities increases that want to evaluate the climatic effects of urban developments. However, the information required to do so is often not easily available. Remote sensing data provides independent, area wide and up-to-date spatial information. Therefore, this contribution addresses the question if remote sensing techniques can help to optimise mitigation strategies for climate change in cities. Several parameters describing the urban climate can be directly mapped by remote sensing, such as albedo and surface temperature. However, the main use of remote sensing is expected in the mapping of the urban land cover and morphology. The urban climate is strongly influenced by the spatial characteristics of the city. Area wide maps of spatial parameters such as impervious surface or vegetation fraction can provide insight in expected climatologic situations because of the strong relationship of these spatial parameters to climate and humidity. Climate models, used to evaluate different planning scenarios, can make advantage of accurate spatial description of the area of interest. However, existing climate models will need adaptation to be able to use the remote sensing data.

## 2 INTRODUCTION

The awareness about climate change and its possible consequences for urban areas is growing. The prospects of global warming will be specifically dramatic in urban areas (KUTTLER, 2004). In Germany this resulted in an increasing interest of planning authorities who want to evaluate the climatic effects of their planning activities. Their objective is to maintain the liveability of cities in the future. With climate changes such as the expected increase of hot summer days (DWD, 2011), it is important to create places with reduced temperatures and to facilitate corridors of fresh air.

To assess the consequences of climate change for urban areas and to develop effective mitigation strategies, information is required on the possible changes of the climate and on the effect of changes in the city structure and land use (new buildings, parks, streets) on the local climate. By combining this knowledge, it can be learned which urban changes will likely aggravate unwanted climatic effects and which urban changes can mitigate them. The local climate depends on the regional climate and the local surface and morphology characteristics, such as the size, number, shape and orientation of buildings and other urban objects, the materials used or the amount and type of vegetation (OKE, 1988a; OFFERLE ET AL., 2007; CHEN ET AL., 2009). The interaction between those variables, determine the actual temperature, the wind speed, humidity and air quality. In table 1 it is shown for a selection of urban spatial characteristics how they contribute to these four main climate surface parameters. Information on these four main climate parameters can be derived directly by using in situ measurements, indirectly by using indicators or based on simulations. In situ measurements, for example by weather stations, are highly accurate and often provide long time series of data. The variation over time is relevant to understand the relations with human activities and seasons or to monitor the change of the situation. However, the spatial variation of the values of the parameters is important to gain an overall impression of the complex climatic structure of the city as well (XU ET AL., 2008). This information can seldom be provided by in situ measurements, because the observational network is often too coarse. Measurements with equipment installed on vehicles are an improvement, but still cannot provide area wide coverage (WENG, 2009). By making use of spatial indicators, parameters such as temperature, humidity etc. can be estimated area wide. Many studies have been carried out to quantify the relationship between the surface parameter and the climate parameter of interest (e.g. WENG ET AL., 2011, ZHANG ET AL., 2009). Finally, powerful tools to study both the actual and future climate are models and simulations. Models allow the assessment of many different situations while requiring a limited amount of in situ measurements. For example, SHASHUA-BAR & HOFFMAN (2003) and ZHANG ET AL. (2004) studied the influence of street and building geometry (street canyons) and trees on air temperature and wind using numerical modelling.

Area-wide spatial knowledge is of crucial importance to understand the climate situation in cities, but such information is often too generalized, outdated or not even available. Remote sensing data provides independent, area wide and up-to-date spatial information on the earth's surface. Remote sensing data is thus suitable for the mapping of surface characteristics which influence the urban climate (see table 1). Hence, this contribution addresses the question to which extend remote sensing can help to find out what the effect of climate change on urban areas will be. For that purpose we provide and discuss examples of relevant remote sensing products from literature and several studies in the city of Munich, Germany.

## 3 MEASURING CLIMATE PARAMETERS

Remote sensing makes use of the electromagnetic radiation reflected or emitted by the Earth's surface (LILLESAND ET AL., 2004). Different surface types reflect, absorb or emit the radiation (light) with different intensity in different wavelengths. This information is used in the analysis of remote sensing data to map different land cover types. The net radiation is an important parameter in the urban energy balance which describes the heat fluxes. The net radiation is the sum of the incoming minus the reflected short-wave radiation (albedo) and the incoming minus the out-going long wave radiation (thermal radiation) (OKE, 1988b).

Surface albedo is a key terrestrial variable controlling the surface energy budget. It is defied as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS, 2011). There are several global albedo products available, such as those derived from the MODIS satellite (SCHAAF ET AL. 2002) or from the Meteosat and GOES satellites (GOVAERTS ET AL. 2008). Although these products are updated regularly (at least weekly), the spatial resolution is very coarse ( > 1 km). For the calculation of the urban energy balance, higher resolution data is required. In RIGO & PARLOW (2007), Landsat data (30 m) is used to derive the albedo of the city of Basel, Switzerland. The objective was to calculate the ground heat flux, which contributes significantly to the development of urban heat islands. To calibrate their models, they used ground measurements. Figure 4c shows an example of the surface albedo for a building block in Munich, derived from airborne HyMap data with a spatial resolution of 4 m.

The thermal radiation measured by remote sensors is usually converted into surface temperature. Surface temperature is important for the estimation of the energy budget and for bio-climatic studies, among others (MITRAKA ET AL. 2012). Figure 1 shows the surface temperature of the city of Munich for a summer day in 2007 as recorded by two different sensors. The whole city is recorded by the space borne Landsat sensor, with a spatial resolution of 60 m. A subset of the city was also recorded by the airborne Daedalus sensor with

| **Urban spatial characteristics** | **Climate surface parameters** | | | |
|---|---|---|---|---|
| | **Temperature** | **Wind speed** | **Humidity and precipitation** | **Air quality** |
| Building structure | ● | ● | ● | ● |
| H/W ratio of street canyons | ● | ● | | ● |
| Sky view factor | ● | | | |
| Land cover | ● | ● | ● | ● |
| Albedo | ● | | | |
| Emissivity | ● | | | |
| Thermal inertia | ● | | | |
| Impervious area | ● | ● | ● | |
| Vegetation fraction | ● | ● | ● | |
| Surface water | ● | | | ● |
| Land use | ● | | ● | ● |
| Traffic density | ● | | ● | ● |
| Industrial areas | ● | | ● | ● |

Table 1: Overview of urban spatial characteristics that influence the four main climate surface parameters. H/W ratio = height/width ratio.

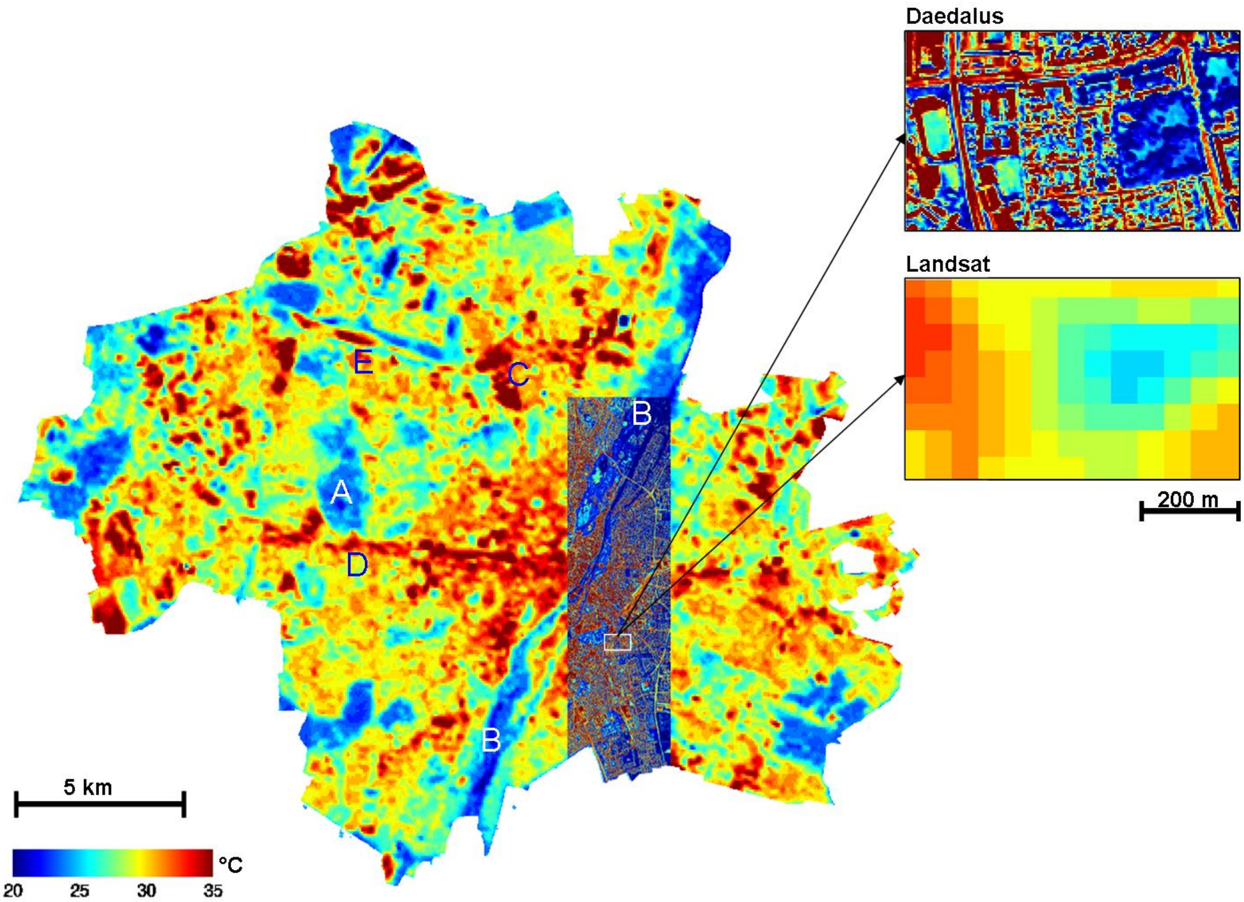


Figure 1: Surface temperature of Munich at a summer day in 2007, mapped by the space borne sensor Landsat (30 m spatial resolution) and the airborne sensor Daedalus (4 m spatial resolution).

a spatial resolution of 4 m. The image shows several interesting thermal patterns. Clearly recognisable as colder areas are for example the large park belonging to the castle Nymphenburg (A) and the flood plains along the river Isar (B). The densely built city center has high surface temperatures, as does the industrial site in the north of Munich (C). Also the two main railway tracks (D, E) with neighbouring industrial and bare surfaces are warmer than their environment and clearly recognisable as line structures. The zoom images on the right show the difference in detail between the two sensors. In the Landsat image almost no differentiation except for a larger park is possible. In the Daedalus image, on the other hand, the differences in surface temperature between buildings, vegetation and roads is clearly visible.

## 4 MAPPING SURFACE CHARACTERISTICS RELATED TO URBAN CLIMATE

As already shown in table 1, many surface characteristics influence the urban (micro) climate. Nine of the twelve characteristics listed in the table can be derived with remote sensing by different sensors. The retrieval of building structure, H/W ratio and sky view factor require a digital elevation model which can be derived from stereo imagery or laser scanning. Commonly, airborne sensors are used because they can provide spatial resolutions that are high enough for this purpose. Land cover, impervious area, vegetation fraction and water can be mapped with a large range of airborne and satellite-based sensors, since also satellite-based sensors provide sufficient spatial resolution for the discrimination of individual urban objects such as buildings. For the measurement of albedo, a sensor is required that records the radiation in a broad range from the visible to the short wave infrared. On the opposite, emissivity requires thermal remote sensing that records the radiation in the long wave infrared.

Since these spatial characteristics can be very well mapped with remote sensing, many studies exist in which the relation of such spatial characteristics with climate parameters are analysed. Most studies are concerned with the climate parameter temperature. For example the relationship with imperviousness (e.g. ZHANG ET AL., 2009; YUAN & BAUER, 2007; XIAN, 2008) and fractional vegetation cover (e.g. JENERETTE ET AL., 2007; WENG ET AL., 2004) has been analysed. Also the relationship of spatial characteristics to the climate parameters wind (OFFERLE ET AL., 2007; ELIASSON ET AL., 2006) or air pollution (WENG &

YANG, 2006) have been studied, although less frequently because the influence of spatial characteristics on these parameters is not as strong and often indirect via changes in temperature.

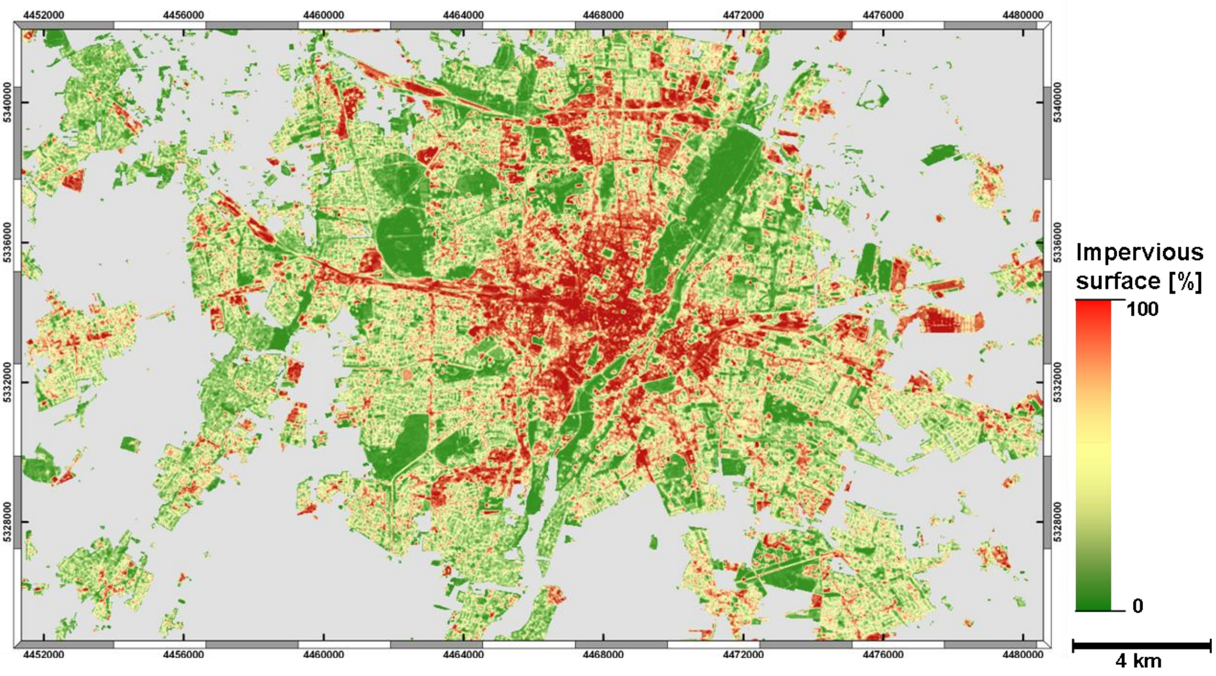


Figure 2: Impervious surface for the city of Munich, derived from space borne Landsat data.

Making use of known correlations, a map of surface parameters such as imperviousness or fractional vegetation cover provides already a lot of information on locations in the city where the (surface) temperature is likely to be higher or where the humidity will be lower. As an example, a map of impervious surface derived from Landsat data and a map of vegetation density derived from airborne hyperspectral HyMap data is shown in figures 2 and 3. They both show the city of Munich. The map of impervious surface in figure 2 has a spatial resolution of 30 m and was derived using a Support Vector Machine approach (ESCH ET AL. 2009). The city center has a much higher percentage of impervious surfaces than the residential areas in the outer districts of the city. The inverse pattern is visible in the vegetation density map (figure 3). The vegetation density is calculated using a spectral unmixing approach and is subsequently aggregated to building block level (HEIDEN ET AL., 2012). Both maps seem to indicate that in the city center higher temperatures can be expected. However, there are several areas within the center where people can retreat if it gets too hot: the small parks (green spots in figure 2) in the northern part of the city center and the large parks along the Isar, forming an SW-NE green corridor.

## 5 SUPPORTING CLIMATE MODELLING

The use of models is common praxis for climatologists and meteorologists. The most well-known examples are of course weather forecasting models. Dynamic models, or forward models, have the possibility of simulating ongoing processes. Because of their predictive capabilities, such models can be used to simulate different scenarios. This is a useful feature for urban planning. It allows the evaluation of climatic effects of planned urban development projects prior to the, often irreversible, realisation of a project. Many different climate models exist. They vary among others in the climate parameters they address, the spatial scale and complexity (ARNFIELD, 2003).

For the evaluation of urban developments, local scale models are most suitable. Examples of local scale urban climate models are MISKAM (EICHHORN & KNIFFKA, 2010), ENVI-met (BRUSE & FLEER, 1998) or MUKLIMO_3 (SIEVERS, 1995). The spatial environment is always one of the input parameters of climate models. Vegetation fraction, imperviousness and surface roughness are some of the parameters commonly used in climate models to describe the environment. Some models assume default values for these parameters. Other models, mainly at global and regional scale, retrieve land cover or land use types from maps or remote sensing data (e.g. GlobCover) and assign to each type a defined set of spatial parameters. Only few models allow for a detailed description of the environment and the according parameters (PINTY

ET AL, 2006). An example of such a model is ENVI-met (BRUSE & FLEER 1998). This model requires a detailed description on the location and characteristics of all urban objects in the modelled environment. In a study carried out in the city of Munich, as many input parameters as possible required by the ENVI-met model were derived from hyperspectral remote sensing and airborne stereo imagery. Table 2 shows, that more than half of the required parameters can be generated on the basis of remote sensing data. Remote sensing comes to its limits when soil or material properties are required. Due to the bird's view it is also not possible to provide data on vertical or hidden structures, e.g. building walls. Also the weather conditions cannot be derived from the remote sensing data. However, the weather conditions can be used for the description of different scenarios, to simulate different (future) climate conditions.

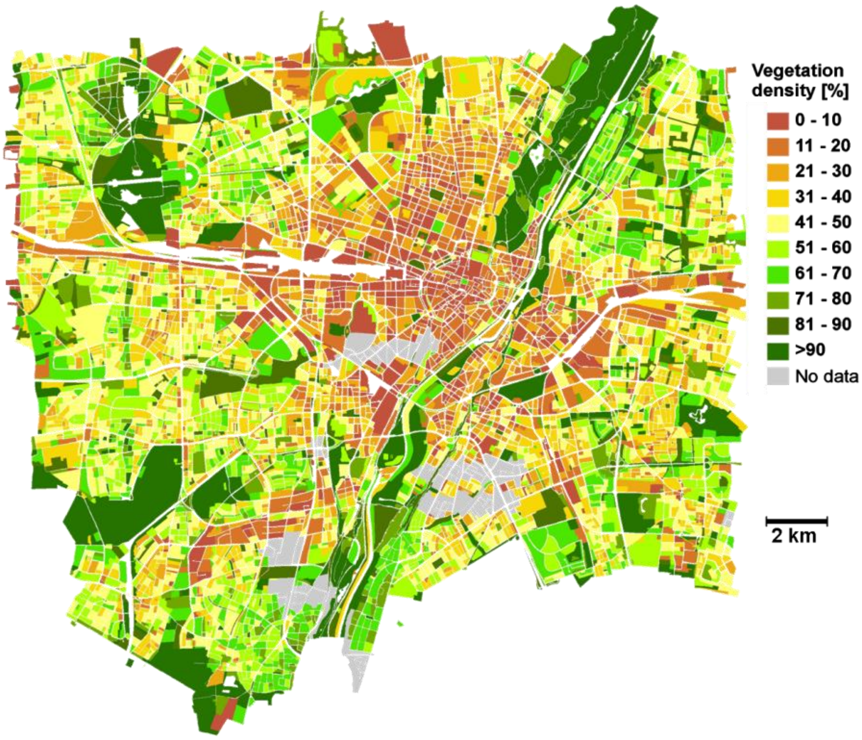


Figure 3: Vegetation density per building block derived from airborne hyperspectral remote sensing data for a subset of the city of Munich.

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

Table 2: Input parameters and their sources required for urban micro climate modelling with ENVI-met

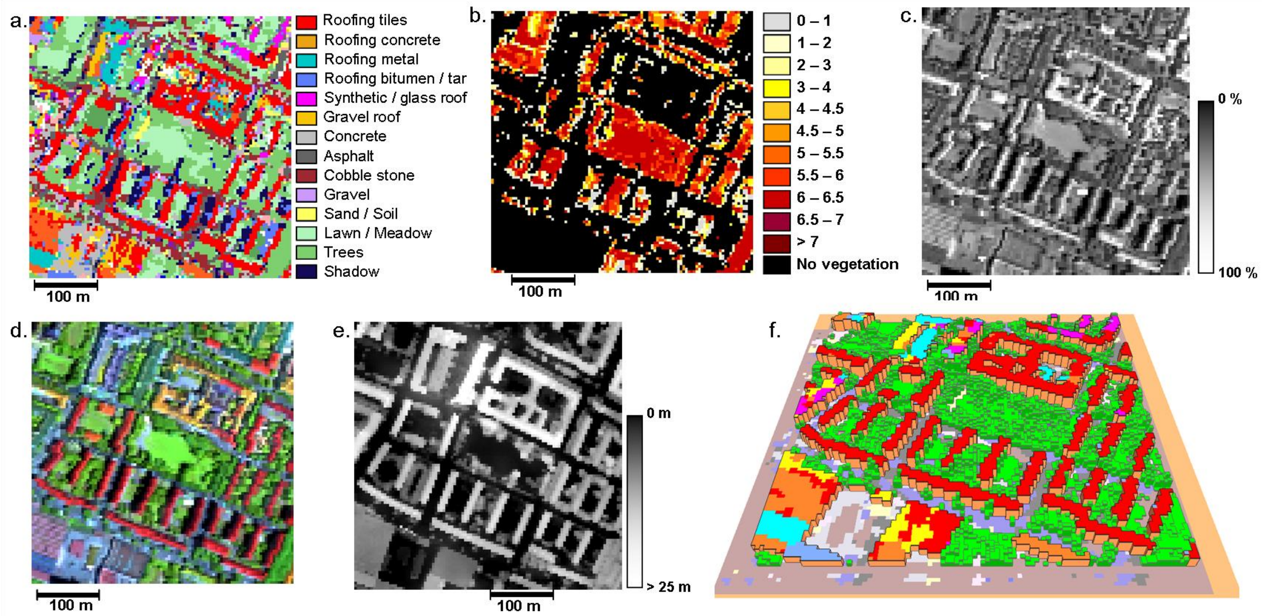


Figure 4: Input data for the micro climate model ENVI-met. Upper line: maps derived from the HyMap data: surface materials (a), leave area index (b) and albedo (c). Lower line: the HyMap subset (d) and DEM subset (e) of the study area and the final 3-D input file for the model (f).

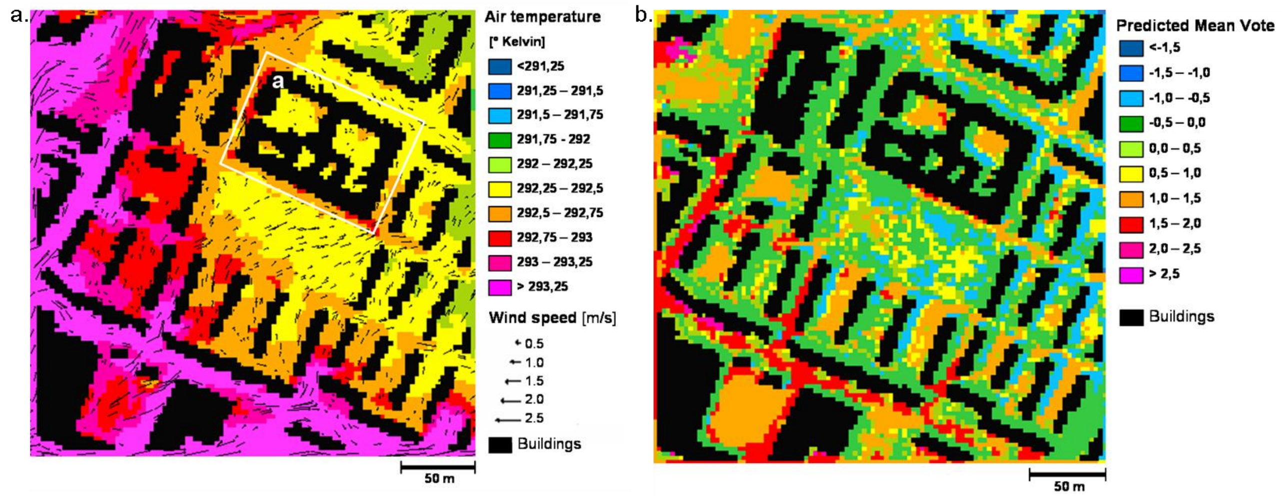


Figure 5: Simulation results of the ENVI-met model using input data from remote sensing: a) air temperature and wind speed, b) the human comfort index PMV.

From the hyperspectral data, the land cover type is derived at the level of surface materials (figure 4a). This airborne data set is also used for the retrieval of leaf area index (fig. 4b) and albedo (fig. 4c). The digital elevation model (DEM) provides the height of the buildings and vegetation (fig. 4e). The methodology is described in detail by HELDENS (2010) and HELDENS & HEIDEN (2010). This results in a 3-D input file for the ENVI-met model (figure 4f). The 3-D file is then used for the simulation of the urban micro climate over 24 hours. Because of the long computation time to date, only a small area of a few building blocks can be simulated at once. Some results of the simulation are shown in figure 5. It shows the simulated air temperature and wind speed at 15:00 at 1.5 m height. In the simulated scenario a south-western wind is assumed. Figure 5a 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 K (19.2 °C) in this building block. At the sun-exposed sides of the buildings the air temperature is higher: around 292.8 K (19.7 °C). It should be noted that the temperature variation within the area is all within 3°. Figure 5b shows another result from the simulations: the predicted mean vote (PMV) at 15:00. The PMV is a human comfort index, which provides information on the well-being of humans. Originally PMV was developed for the assessment of indoor climate by (FANGER, 1970), but was then adapted for assessment of the outdoor climate (BOUYER et al., 2007). 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). Figure 5b 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).

## 6 DISCUSSION AND CONCLUSION

In the previous sections, a range of remote sensing products has been shown that are relevant for urban climate analysis. The large variety of sensors that are available enables the mapping of a vast number of parameters. The area-wide and large spatial coverage of remote sensing data enables the analysis of complete neighbourhoods or even cities at once. Frequent images acquisitions and automated mapping algorithms allow the fast updating of maps. Can remote sensing help to optimise mitigation strategies for the influence of climate change on urban areas? The examples in the previous sections show that except for albedo and surface temperature, remote sensing products provide only indirect information on the urban climate. In order to draw conclusions on the urban climate, in situ measurements or climate simulations are indispensable. But, since the spatial characteristics play an important role in the urban micro climate, remote sensing can certainly contribute to the assessment of the urban micro climate and its interaction with the urban environment. The combination with remote sensing data seems especially valuable for the support of in situ measurements and for the support of climate modelling.

Remote sensing-based mapping of impervious surface, fractional vegetation coverage etc. can provide a first impression where unwanted climatic conditions are likely to occur first. These locations can then be selected for in situ measurements or climate simulations. Because of the frequent and large spatial coverage of remote sensing data, detailed monitoring of urban areas is possible. This way, climatologically undesirable urban developments can be recognised fast and without extensive simulations, by using relevant spatial parameters as indicators. Time series dating back to the 1970s allow us to learn from changes in the past. Combining a time series of spatial parameters, e.g. impervious surface, with long time measurements of air temperature will provide valuable information.

A further promising application of remote sensing products for climate analysis is to use them as input data for climate modelling at different scales. This supports a fast and flexible generation of the input data for such models and enables the models to simulate the actual situation. By simulating different scenarios, it can be assessed which urban developments successfully mitigate unwanted climate change effects. However, existing climate models will need adaptation to be able to use the remote sensing data.

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