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A Bayesian Maximum Entropy scheme for the assimilation of mobile recordings with simulations of urban micrometeorological data

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Abstract: This paper proposes a framework for assimilating urban temperature measurements with simulations of an urban micrometeorological model. Data assimilation, a technique that incorporates observations into a computer model of a real system, is commonly applied in global and regional weather forecasting and an emerging issue in urban meteorological modelling. For that purpose, we suggest applying a novel approach, the Spatiotemporal Epistemic Knowledge Synthesis (SEKS). It combines simulations of a thermodynamic urban climate model, as general knowledge base, with a model output statistics (MOS) of observations, as site-specific knowledge base, by means of Bayesian Maximum Entropy (BME) inference resulting in posterior distributions of the parameters.

Examining real meteorological situations in an urban quarter by mobile observations with instruments in a backpack and by simulations with the urban climate model ENVI-met, we illustrate how mobile meteorological measurements can considerably up-value simulated urban meteorological fields (such as air temperature). Performance measures demonstrate that (a) the output of the simulation model is improved by an assimilation of observations, and (b) the data gathered only at a path are extrapolated to a whole urban region, for which a temperature map together with information about the confidence is provided.

A conclusion is that individuals moving throughout a city are ideal explorers for the urban meteorological conditions. Recent technical developments facilitating individual-based temperature recordings, e.g. based on mobile phones, might be beneficially combined with the suggested data assimilation techniques and can help to construct urban maps of meteorological parameters. In consideration of the changing climate in cities, actual urban heat maps can be helpful for personal adaptation measures.

Keywords: urban meteorological conditions; data assimilation; mobile measurements; crowdsourcing, urban exploration

1. INTRODUCTION

In cities, the meteorological conditions are considerably modified by the urban structure. The resulting variations are larger than in the surrounding regions and can directly impact the urban inhabitants. Walking in the city, an individual experiences e.g. the thermal conditions at many different locations and, in this way, collects a sample of meteorological observations. This approach is applied in the techniques of mobile meteorological observations utilizing cars, bikes, or just pedestrians for an exploration of the urban meteorological conditions.

The question arises, how informative a sample registered in this way might be for the weather conditions in the surrounding environment that was not sampled. The spatial distribution of, e. g. temperature, arises from the urban structure and the prevalent weather situation and can be simulated by help of a suitable urban climate model. The informative value of mobile observations might be considerably improved when they are combined with such simulations in the frame of a data assimilation technique.

Data assimilation techniques are commonly applied in numerical weather forecasting and have the general aim to align the run of a numerical weather model as close as possible with the development of meteorological parameters in the real atmosphere. Applications range from the complex involvement of observations into the forecasting model to the statistical post-processing of forecasted data subsequent to their calculation in the numerical model (Kalnay, 2002). Combining a model with observations has the advantages that, firstly, the model output is directed and improved by the measurements and, secondly, gaps in the observations are meaningfully interpolated by the model output. For many years, the assimilation of meteorological data with model simulations is a common technique at the macro- and meso-scales (Giannaros et al., 2013; Chen et al., 2011; Liu et al., 2006).

An interesting and so far insufficiently considered application is the combination of mobile measurements of meteorological parameters with urban micrometeorological simulations. In currently available models, the latter cannot be influenced in their run after an initialization of the parameters with real values. In result the model can drift apart from reality. Such unrealistic model simulations might be avoided when observations are included. Unfortunately, state-of-the art urban meteorological models do not allow for a continuous input of observations during the runtime. Therefore, we suggest post-processing the simulations with a statistical data assimilation procedure. One purpose of the paper is to demonstrate this approach in a realistic situation and to assess its performance.

A second aim of the paper is the utilization of the suggested approach for the extrapolation of measurements. Mobile recordings of atmospheric conditions, which are made in urban areas with increasing interest, provide just point observations. Here an extrapolation to other space-time points (e.g. an urban quarter) is desirable. We apply our approach to real measurements and quantify the quality of these extrapolations.

2. MODELLING APPROACHES AND DATA

In this paper, we suggest the application of a Bayesian data assimilation methodology, the Spatiotemporal Epistemic Knowledge Synthesis (SEKS, Christakos, 2000), in combination with urban temperature data simulated by the thermodynamic micrometeorological model ENVI-met (www.envi-met.org). In an evaluation procedure we test the suitability of the suggested approach (a) for the improvement of the simulation output of the urban meteorological model (data assimilation) and, (b) for calculating extrapolations of mobile measurements to a quarter of the urban region.

ENVI-met is a free three-dimensional prognostic climate model to simulate the interactions between urban surfaces (including buildings and streets), vegetation and the atmosphere on the micro-scale (Bruse, 2009). It is partitioned into a three-dimensional main model solving the basic thermodynamic and momentum equations (e.g. non-hydrostatic Navier-Stokes equations). Within the core model the structure of buildings, different kinds of surfaces and plants are defined. To include the vegetation processes in the simulation of urban meteorological parameters, additional source or sink terms are added to the basic equations (Bruse and Fleer, 1998). For calculating the heat transfer between the urban surfaces and soils, a simple one-dimensional soil model is used.

The user of ENVI-met has to implement the geometry of the study area into the area-input file including buildings, plants and different surfaces. In addition there is an initial file with start values. These parameters include, among others, air temperature and relative humidity at 2500 m height, wind speed and wind direction at 10 m height, cloud coverage, constant inside temperature of all buildings, albedo of roofs and walls, soil temperature and moisture in three depths.

The meteorological data utilized here are derived from official sources and characterize the general weather situation in the study region. While these data represent the boundary conditions for the prognostic model covering an urban quarter, the mobile temperature measurements within this area have a strong spatial variability. The latter is treated by a statistical technique that is applied here to separate the measurement errors from the variability due to the local urban structure (represented by the simulations of the prognostic model).

Spatiotemporal Epistemic Knowledge Synthesis (SEKS) is the general framework under which the methods of Modern Spatiotemporal Geostatistics (MSG, Christakos, 2000) have been developed. They provide powerful techniques for generation of informative, high-resolution maps of atmospheric variables in a composite space–time domain (Christakos, 2002). Let the vector $\vec{p} = (\vec{x}, t)$ define a point in the space–time domain and $\vec{T} = T(\vec{p})$ representing the spatiotemporal random field of temperature. Predictions are made with the Bayesian Maximum Entropy (BME) method in a high spatial resolution that is essential to understanding and predicting the personal temperature exposure of the inhabitants living and moving inside this region (Schlink et al., 2014).

Our study was exemplified for temperature data measured in a quarter in Leipzig, Germany, the so-called Waldstraßenviertel. For the ENVI-met simulations this region was covered by a grid of 225 x 225 cells (Figure 1, grid-cell size 5 x 5 m²). The investigation area is characterized by a large park in the north-eastern part. Low-density residential areas can be found adjacent to the park in the eastern part of the region. In contrast, the western and southern parts of the Waldstraßenviertel are dominated by open (and also partially closed) built-up block structures (predominantly multifamily buildings in open or closed perimeter developments with green spaces in the middle of the blocks, vacant spaces open the perimeter character; see a previous study by Franck et al., 2013).

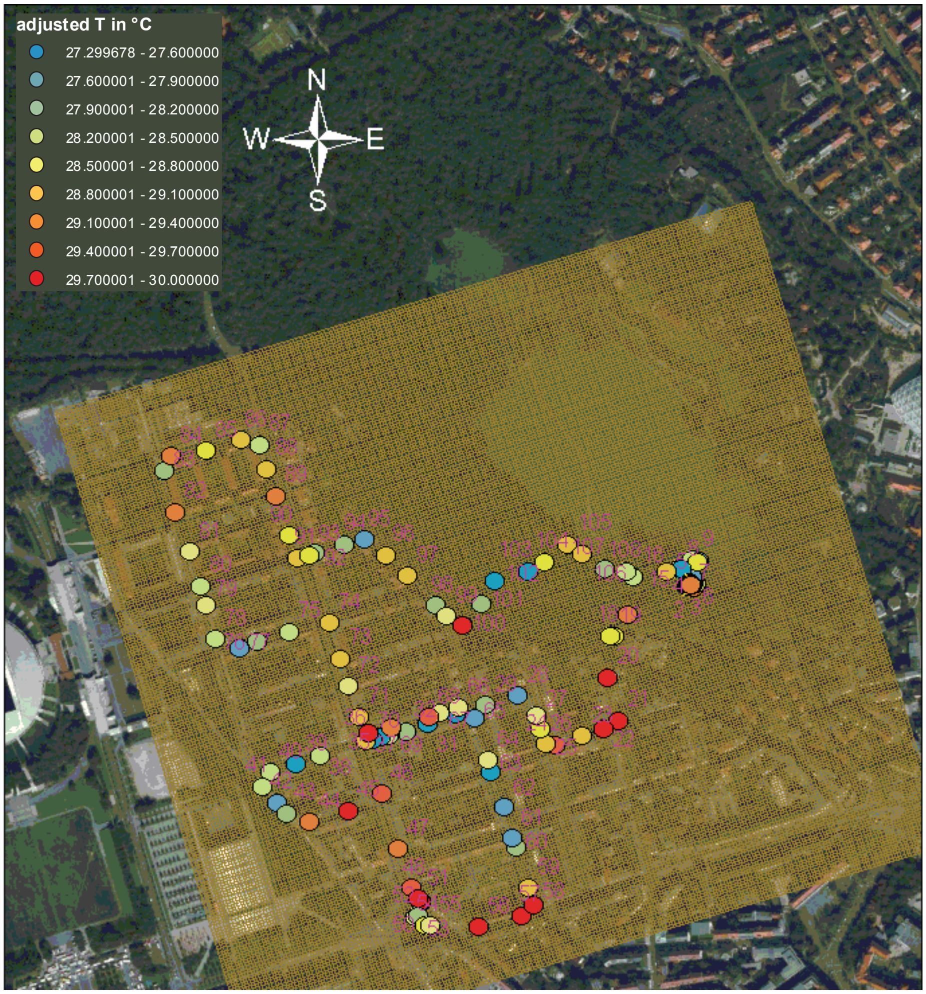

Figure 1: Temperatures at the numbered points of mobile measurements in Sept. 2013 in the Waldstraßenviertel and the grid applied in ENVI-met urban temperature simulations (all temperature values are adjusted to 16:00 CEST).

Mobile measurements of air temperature and relative humidity at 1.5 m above ground have been stored every minute (sensor TESTOSTOR 171 with data logger in a ventilated tube protecting against solar radiation, company Testo, Germany, accuracy: ±0.1 K), together with the corresponding geo-coordinates (GPSmap 60CSx, Garmin, accuracy: ≤10 m) within a measurement campaign (Figure 1) on September 7th, 2013, (14:20–16:22 CEST); time values are given in Central European Summertime (CEST = UTC + 2 h). As the temperature observations $T(x,t)$ lasted about two hours, we removed the temporal trend, $trend(t)$, by means of a high-pass filter (cut-off frequency = 1/80min) and adjusted all recordings to 16:00.

Usually, meteorological observations are linked with collocated simulations of a numerical model by means of model output statistics (MOS), for which we applied a regression approach here. From the simulation output of ENVI-met we identified the significant predictor variables air temperature 1.5m above ground (T_{sim} in °C), rel. humidity 1.5m above ground (rH_{sim}), and ground temperature ($T_{G,sim}$ in °C) for which the Akaike Information Criterion was minimal. A MOS equation was fitted for the observations on the path $T_{obs} = a_0 + a_1 \cdot T_{sim} + a_2 \cdot rH_{sim} + a_3 \cdot T_{G,sim}$ with $\hat{a}_0 = 13.656 \pm 4.270; \hat{a}_1 = 0.348 \pm 0.135; \hat{a}_2 = 0.058 \pm 0.020; \hat{a}_3 = 0.048 \pm 0.017$; $R^2 = 55\%$. This MOS was applied to the whole ENVI-met simulation output and generated improved temperature predictions: $\hat{T}(x) = \hat{a}_0 + \hat{a}_1 \cdot T_{sim}(x) + \hat{a}_2 \cdot rH_{sim}(x) + \hat{a}_3 \cdot T_{G,sim}(x)$.

3. RESULTS

Simulations of the urban climate model ENVI-met result in typical patterns of temperature in the study area (Fig. 2), which is halfway between downtown (south-east to the Waldstraßenviertel) and a large urban park region in the northeast.

Two different procedures have been applied to evaluate the quality of the suggested data assimilation technique. Firstly, simulated data at the path locations have been taken as input data to the SEKS procedure. The latter combines these “measurements” with a statistical model represented by the mean temperature field and the covariance function derived from the simulations. By the use of Bayesian inference (BME) the posterior distributions for the temperature are calculated for the total urban quarter. This extrapolation differs only slightly (<0.6 K) from the original temperature distribution generated with simulations (see temperature differences in Figure 3).

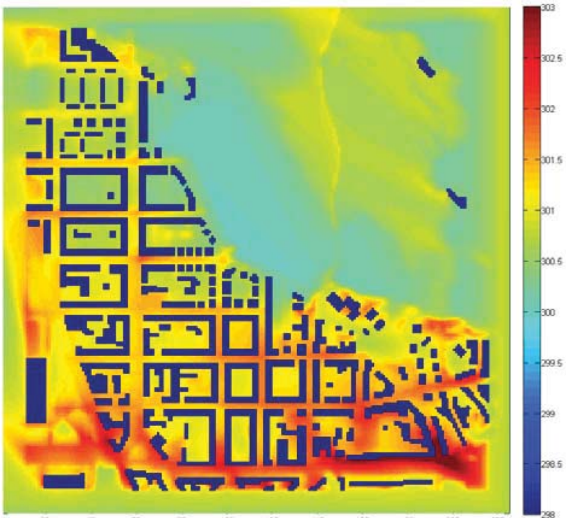

Figure 2: Simulated temperature at 1.5 m height in the study region (Fig. 1) at 16:00 CEST. Wind from east-southeast (99°);
N direction rotated by 17°; temperature scale ranges from 298 … 303 K (i.e. 25 … 30 °C).

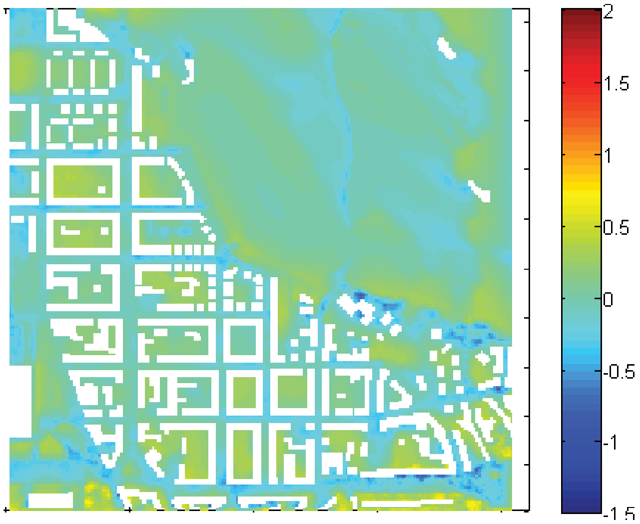

Figure 3: Temperature difference (in K) between ENVI-met simulation and BME-prediction maps. Buildings marked in white; N direction 17° rotated.

In a second evaluation procedure we utilised the mobile recordings of temperature in the urban quarter along the path. Detrended data from the first half of the path $T_{\text{detrended}}(x, t = 16:00) = T(x,t) - trend(t) + trend(t = 16:00)$ were used as input and combined with the statistical temperature model (consisting of mean field and covariance function) to calculate an extrapolation to the total urban quarter. Though the general structure of the predicted/extrapolated temperature field (P) is reasonable, the accuracy of these predictions is reduced compared to the observations (O): var(P)=14.68 (compared to var(O)=0.18), MAE(O,P)=3.22, RMSE(O,P)=4.29, corr(O,P)=0.17.

4. CONCLUSIONS

Urban meteorology results from an interaction of the regional weather conditions (synoptic situation) with the urban built environment. The latter is human-designed and in this way people can deliberately modify meteorological conditions in their immediate environment. The most remarkable effect of the urban structure on local meteorological conditions is the Urban Heat Island that becomes manifest in higher nocturnal air temperatures down town than in the surrounding countryside.

In general, urban air temperatures can vary strongly even at very short distances, especially during calm and high pressure weather situations. During these so called autochthonous situations the local meteorological parameters mirror the local geographical conditions, such as the imperviousness of the ground, the orography of the terrain, or the albedo of the surfaces. In contrast, during allochthonous situations the strong winds mix the air up and impede the formation of site-specific meteorological parameters.

The high pressure weather situations are conducive to the formation of heat waves that are especially stressful in urban regions. For such extreme events it is important to know about the local variability of temperature and this can help individuals to avoid high exposure and facilitate urban planning decisions. Utilizing modern information technologies, such as mobile phones and miniature sensors, people can actively contribute to the exploration of urban meteorological conditions. About one hundred years ago, mobile observations have been suggested as a technique to record temperature profiles along an urban transect.

Unlike measurements, models for the simulation of urban meteorological parameters are still scarce and existing approaches want for refinements, due to the very complex interactions of the atmosphere and the urban built structure. Both, the modelling as well as the assimilation of model-simulations with observations, are not nearly as advanced for the urban meteorology as for the numerical weather forecasting at the synoptic scale.

In our study we suggested a technique that assimilates data gathered with mobile measurements into the urban meteorological data simulated with the model ENVI-met. In the Bayesian sense, this assimilation procedure combines the prior knowledge of the simulated urban temperature field with observational data and results in posterior information about the real distribution of temperature in the studied urban region. For such mobile explorations we conclude that

- Though mobile measurements provide data only at a limited number of locations in an urban area, they can be extrapolated and interpolated to a much larger region by help of statistical techniques such as the Bayesian Maximum Entropy approach. To specify the statistical model (average field, covariance function) simulations of an urban micrometeorological model are helpful.

- While a deterministic micrometeorological model provides high resolution fields of urban atmospheric parameters, these simulations always deviate from the real situation. For that purpose, simulated and measured data should be assimilated, resulting in an improved field.

- The collection of environmental data by means of mobile recorders, no matter if they are instruments in a backpack or small sensors carried in bikes, cars of the human body, contributes essentially to the exploration of urban environmental conditions. Random fluctuations, inherent in such mobile recordings, are adequately handled within the statistical data assimilation procedure.

- In a post-processing step, simulated atmospheric parameters are linked with measurements in a regression equation. In our study, we used 54 data points for model fitting and further 54 data points for the assessment of the extrapolation quality. As the regression accounts for just 55% of the total variability it should be improved in further research work.

The suggested approach is transferable to other urban environmental parameters, such as air quality and noise. Therefore this method for data assimilation can be a valuable tool combining mobile measurements taken, for example, with miniature devices (and even with smartphones – so called Mobile Crowdsourcing techniques) with spatiotemporal simulations of computer models.

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