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Sensor lag correction for mobile urban microclimate measurements

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ABSTRACT

Some uncertainty in mobile microclimate observations stems from sensor lags. This is especially critical in mobile transect campaigns conducted in urban areas, where observations have to be related to the quickly varying complex surroundings of the sensor, which becomes difficult if the sensor has a high time constant relative to environmental scale and sensor velocity. We present an optimized method for sensor lag correction using a transfer function, based on the optimization of three correction parameters: moving average window size, transfer function setup, and linear time shift. We evaluate the method by comparing the corrected temperatures measured with "slow" Resistance Temperature Detectors (RTD) to a ground truth provided by synchronous measurements with thermocouples that have a time constant of less than one second. Theoretical assumptions about the correction procedure design are substantiated by the optimization procedure, which yields consistent results for mobile transect data sets recorded at different times of day and in different seasons.

1. Introduction

Mobile transect measurements are used in urban climate studies to retrieve information about canopy-layer urban heat island characteristics (Heusinkveld et al., 2014; Sofer and Potchter, 2006; Murphy et al., 2011; Sun et al., 2009), park cool island intensities (Chow et al., 2011), to more generally investigate the effect of land use configurations on urban microclimate (Stabler et al., 2005; Brazel and Johnson, 1980), and to assess thermal comfort (Vanos et al., 2012). In all of these applications, the sensors need to accurately sample the microclimate in a dynamically changing physical environment. The combined effects of sensor inertia, air speed, sampling frequency, and platform velocity determine the spatial resolution of the transect data (Achberger and Bärring, 1999).

Sensor inertia is dependent on the time constant τ_{63}, which is defined as the time a sensor needs to adapt to 63% of an impulse change (Foken, 2006; Achberger and Bärring, 1999). For air temperature sensors, this impulse is a change in the ambient temperature, which can occur frequently during a mobile transect run. With larger time constants, the temperature curve recorded by a sensor is smoothed because local minima and maxima cannot be resolved (Achberger and Bärring, 1999; Mayer et al., 2009). Mayer et al. (2009) and Foken (2006) refer to this error as the *dynamical error*, causing an attenuation of the measured air temperature amplitudes (Mayer et al., 2009). Mayer et al. (2009) also state that *lag-times* can complement this error. As the dynamical error, they are caused by the inertia of the entire measurement system (sensor and housing) and provoke temperature differences to be registered later than they actually appear (Mayer et al., 2009).

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Although sensor lag effects also impact stationary measurement systems (Harrison, 2010, 2011), they are generally an important factor when a sensor is moved through space (Mayer et al., 2009). Studies on sensor inertia have thus been carried out in the context of radiosonde or airborne temperature measurements, in which the sensor moves at very high air speed and velocity (McCarthy, 1973; Inverarity, 2000; Mahesh et al., 1997; Foster and Chan, 2012; Rodi and Spyers-Duran, 1972; Jacobi et al., 1995; Miloshevich et al., 2004). Frequently, it is assumed that the sampled temperature is a convolution between the true temperature and some transfer function, e.g. the time-derivative of the impulse response function using the time constants of the sensor and its housing (McCarthy, 1973; Inverarity, 2000; Rodi and Spyers-Duran, 1972) or solely the time constant of the sensor (Achberger and Bärring, 1999). The transfer function can then be interpreted as a filter for the true temperature, i.e. the convolution of the true temperature and the transfer function yields the measured temperature. Thus, *deconvolution* of the measured temperature results in the true temperature (McCarthy, 1973; Inverarity, 2000; Foster and Chan, 2012).

Studies on sensor lag correction for ground-based, micrometeorological mobile measurements and the verification of the approaches from radiosonde or aircraft measurements for this setting are rare (Mayer et al., 2009). Mayer et al. (2009) successfully demonstrate the applicability of the deconvolution approaches by Inverarity (2000) and McCarthy (1973) to vertical measurements conducted with an elevator tower. They found good agreement between the corrected elevator measurements and the stationary measurements conducted at different heights on a nearby mast. In addition, they developed a simpler correction scheme for two time constants that relies on the subsequent application of a correction scheme to the measured time series, using the time constants of the probe and its housing, achieving similar good results for their simpler correction procedure (Mayer et al., 2009).

Hübner et al. (2014) and Achberger and Bärring (1999) investigate correction procedures for horizontally moving sensors during mobile transects in a micrometeorological context. Hübner et al. (2014) installed a horizontal mobile measurement system based on a garden railway perpendicular to a forest edge and examine how the correction procedure using a linear adjustment of the impulse response function can reproduce the step-change in air temperature at the transition between forest and clearing. Achberger and Bärring (1999) use a correction filter based on the combination of a low-pass-filter and the time-derivative of the impulse response function, similar to McCarthy (1973) and Inverarity (2000). To verify their approach, they compare the corrected air temperature to the values recorded by a nearby stationary sonic anemometer. They are able to bring the power spectra of the two air temperature time series into accordance, although the different spatial positions of the two sensors pose restrictions on the direct comparability of the two data sets.

In this study, we apply the approach for sensor lag correction reported by Achberger and Bärring (1999) to an urban microclimate setting, using moving average as a low-pass filter, and adding a linear shift of the corrected time series. The correction procedure is carried out for air temperature, which is one of the most important variables for urban heat island (Stewart, 2011) and micrometeorology studies. Air temperatures at two different heights were measured using Resistance Temperature Detectors (RTD) and Fine-Wire Thermocouples (FWT) simultaneously while moving a sensor platform through a residential area in the Phoenix Metropolitan Area. The mobile measurements were conducted as part of a larger project, following the goal to observe space and time variations in intra-canopy microenvironmental conditions as a basis for empirical and process-based model development. In this paper, we describe how measurements with relatively slow sensors (in our case RTDs) can be corrected to estimate high-resolution observations (conducted with FWTs) in an urban environment.

2. Materials and methods

2.1. Study site

The data set used to conduct this study was recorded at Power Ranch, a master-planned community in Gilbert, Arizona, USA (33.27 N, −111.69 W, 406 m a.s.l.). According to the U.S. Census Bureau Population Estimate for 2014, Gilbert has 239,277 inhabitants (United States Census Bureau, 2015a) and a land area of 176.02 km^2 (United States Census Bureau, 2015b). The city is located in the southeastern part of the Phoenix Metropolitan Area (Fig. 1), situated in the northeastern Sonoran Desert. The climate in Phoenix is hot and semiarid, with mean daily minimum temperatures ranging from 7.1 °C in December to 28.1 °C in July, and mean daily maximum temperatures ranging from 19.6 °C in December to 41.0 °C in July. The average annual precipitation is 207.7 mm (World Meteorological Organization, 2014).

As summarized by Chow et al. (2012), the Phoenix Metropolitan Area comprises several urban climate features, which have been investigated in various studies during the last decades. One of these features is a pronounced Urban Heat Island (UHI) effect, which is most intensive at night and during clear conditions (Chow et al., 2012; Fast et al., 2005; Sun et al., 2009). The UHI intensity in the Phoenix Metropolitan Area is not negatively affected by wind speeds up to a certain threshold (Sun et al., 2009; Fast et al., 2005), which might be due to the katabatic wind flow induced by the mountains located to the east and south side of the Phoenix Metropolitan Area (Sun et al., 2009). The katabatic winds cause a transition of wind directions at night, bringing cooler air from the mountains down to the valley and thereby intensifying the urban–rural temperature differences. They can thus be seen as a distinct feature of the climate in the Phoenix Metropolitan Area (Chow et al., 2012; Brazel et al., 2005; Sun et al., 2009). In addition to that, the dry air in the desert city causes a high evaporation potential, leading to lower air temperatures in and around vegetated areas (Chow et al., 2012, 2011; Jenerette et al., 2011; Declet-Barreto et al., 2013).