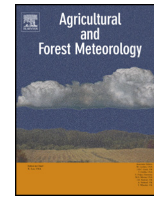
Agricultural and Forest Meteorology 189–190 (2014) 36–47

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Thermocouple frequency response compensation leads to convergence of the surface renewal alpha calibration

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ARTICLE INFO

Article history:
Received 12 August 2013
Received in revised form
17 December 2013
Accepted 7 January 2014

Keywords:
Coherent structures
Response time
Sensible heat flux density
Spectral attenuation
Structure function
Temperature ramps

ABSTRACT

Ramp-like shapes in the turbulent scalar trace are the signature of coherent structures, and their characteristics (i.e., amplitude and duration) are resolved via a structure-function model for use in the surface renewal flux calculation. The potential for surface renewal to provide inexpensive sensible heat flux measurements has not been fully realized because this method has required calibration against eddy covariance or other more expensive flux measurement techniques. The calibration factor alpha is ideally 0.5, but a broad range of values have been reported in the surface renewal literature. Although it has been hypothesized that the sensor size, and hence sensor frequency response characteristics, influence alpha, no effort has been previously made to compensate the thermocouple signal in surface renewal measurements. We evaluate methods for compensating the frequency response of a thermocouple in the time domain and the frequency domain, and we present a novel method for compensation in the lag domain (i.e., compensating the structure function directly). We evaluated the compensation procedure as it affects the resolution of ramp characteristics at both the smallest and the second smallest scales of ramp-like turbulent shapes. The surface renewal sensible heat flux estimates from the compensated robust thermocouples (76 μm diameter wire) agree well with the estimates from the compensated fragile thermocouples (13 μm diameter). Using both the data collected for the present experiment and a meta-analysis of data in the surface renewal literature, we correct the surface renewal estimates for thermocouple frequency response characteristics to obtain alpha calibrations that converge to close to the predicted value of 0.5. We conclude that the frequency response characteristics of the thermocouple are the prevailing influence on the alpha calibrations reported in the literature.

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1. Introduction

Thermal inertia associated with thermocouple heat capacity attenuates the high frequency components of a measured temperature signal. The frequency response characteristics of fine-wire thermocouples can be compensated using time constants (e.g., Scadron and Warshawsky, 1952; Ballantyne and Moss, 1977) based on semi-empirical heat-transfer laws for cylindrical and spherical bodies immersed in turbulent fluid environments (King, 1914; Collis and Williams, 1959). Eddy covariance methodology has previously adopted the thermocouple frequency response compensation (Moore, 1986), but the application of the compensation for surface renewal sensible heat flux estimation has not been investigated.

Surface renewal is an inexpensive alternative to eddy covariance for measuring sensible heat flux density because it requires only a fast-response air temperature sensor (Paw U et al., 1995). Ramp-like shapes in turbulent air temperature time series data are the signature of the coherent structures that dominate surface-layer energy and mass exchange (e.g., Gao et al., 1989). The amplitude and period of the ramps are resolved using the Van Atta (1977) structure function procedure and can be used to calculate the sensible heat flux density in the surface renewal paradigm (Paw U et al., 1995; Spano et al., 1997a). Surface renewal flux measurements, however, require calibration to account for the linear bias in the data (Paw U et al., 1995). The calibration factor alpha is obtained from the slope of the regression forced through the origin of a standard for sensible heat flux (generally taken as eddy covariance measurements) versus un-calibrated surface renewal sensible heat flux measurements. It is hypothesized that the alpha calibration accounts for the uneven heating within the coherent structure that arises from the non-uniform vertical distribution of heat sources in the plant

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0168-1923/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.agrformet.2014.01.008

canopy (Paw U et al., 1995). Assuming a linear decrease in heating from the canopy top to the ground, where no heating occurs, Paw U et al. (1995) predicted an alpha calibration of 0.5. However, a broad range of alpha calibrations has been reported in the surface renewal literature over a variety of surfaces, instrumentation, experimental design, and processing scheme (e.g., Paw U et al., 1995, 2005; Snyder et al., 1996; Spano et al., 1997a, 2000; Chen et al., 1997b). As a result, it has been hypothesized that the alpha calibration also accounts for other physical processes, such as sensor frequency response characteristics (Paw U et al., 1995), micro-scale advection (Paw U et al., 1995), the coherent structure microfront duration and its impact on ramp resolution models (Chen et al., 1997a), effective coherent structure dimensions (Spano et al., 1997a; Chen et al., 1997b), and embedded, multiple scales (Shapland et al., 2012a,b).

Compared to finer diameter (13 and 25 μm) thermocouples, the relatively large 76 μm diameter sensors are more rugged, and therefore are more convenient for field experiments despite their slower response times. Duce et al. (1997) demonstrated a reduction in the magnitude of the surface renewal flux estimation when the air temperature data were collected using 76 and 25 μm diameter thermocouples compared to 13 μm diameter thermocouples. The results of this study varied by structure function time lag and the authors did not attempt to compensate the thermocouple signal. Even if Duce et al. (1997) had compensated the thermocouple signal, the structure function time lag effect may have made it difficult to draw conclusions about the compensation procedure. Chen et al. (1997a) identified the structure function time lag associated with the coherent structure microfront duration as the appropriate time lag for resolving ramp characteristics from data with a single ramp scale, and Shapland et al. (2012a) identified the structure function time lags for resolving ramp characteristics from data with two ramp scales. These developments have made it possible to characterize and correct the underestimation of surface renewal sensible heat flux density estimates due to high-frequency signal attenuation.

We investigate in this paper the accuracy of different approaches to determining the time constant and compensating the thermocouple signal for the resolution of air temperature ramp characteristics and estimation of surface renewal sensible heat flux. Time constants based on the measured thermocouple wire diameter and the mean wind velocity accurately compensate the signal, yielding the dimensions of both the small-scale embedded ramps (i.e., Scale One; Shapland et al., 2012a) and the larger scale ramps (Scale Two). We develop new methods for compensating the structure function directly and for estimating the ramp signal to noise ratio. Using data collected over bare soil and a sorghum canopy with thermocouples of various sizes and by performing a meta-analysis of the surface renewal literature, we demonstrate that the alpha calibration converges to close to its theoretically predicted value of 0.5 once the surface renewal measurements have been compensated for thermocouple frequency response characteristics.

2. Theory

2.1. Surface renewal and structure function analysis

In the surface renewal paradigm, the amplitude and period of the ramp-like patterns in scalar turbulence data are used to calculate the scalar flux density (Paw U et al., 1995). For example, the sensible heat flux density is calculated as follows:

$$H_{SR} = \alpha z \rho C_p \frac{a}{(d+s)} \tag{1}$$

where H_{SR} is the surface renewal sensible heat flux (W m^{-2}), α is the alpha calibration, z is the measurement height (m), ρ is the density of air (kg m^{-3}), C_p is the specific heat of air (J K^{-1} kg^{-1}), ramp amplitude, a is the temperature ramp amplitude (K), d is the gradual rise period (s) of the temperature ramp, s is the quiescent period (s) of the temperature ramp, and the temperature ramp period $(d+s)$ (s) is the sum of the gradual rise period and the quiescent period. Shapland et al. (2012a,b) expanded the original surface renewal concept of only one scale of turbulent scalar ramps to more than one scale (Fig. 1).

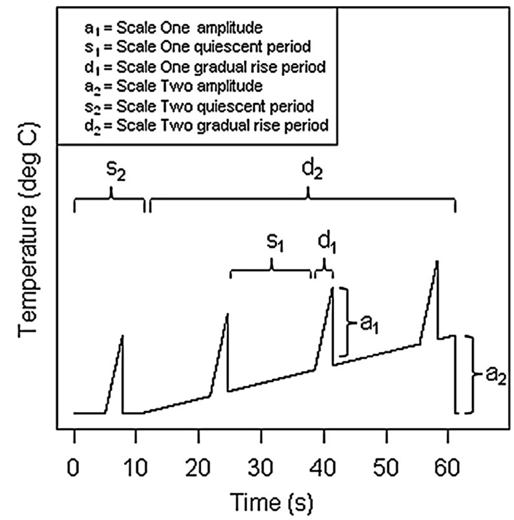

Fig. 1. A two-scale ramp model with an intermittent Scale One (smaller scale) ramp.

The Van Atta (1977) structure function procedure is used to resolve the ramp characteristics for the surface renewal calculation (Spano et al., 1997a; Shapland et al., 2012a,b). The structure function is the mean value of the time difference of a scalar taken to some power.

$$\overline{S^n(r)} = \frac{1}{L}\int_0^L [T(t) - T(t-r)]^n \, dt \tag{2}$$

where $\overline{S^n(r)}$ is the nth-order structure function, L is the length of the time series (s), T is the air temperature (or any scalar), t is time (s), and r is the time lag (s). Detailed descriptions of the Van Atta (1977) procedure for resolving the ramp characteristics from structure function data can be found in Van Atta (1977), Spano et al. (1997a), Chen et al. (1997a), and Shapland et al. (2012a).

2.2. Thermocouple frequency response

The response characteristics of a thermocouple are described by a first-order differential equation, because a single form of energy storage, i.e., the thermal inertia of the sensor, is dominant.

$$T_o(t) + \tau \frac{dT_o}{dt} = T_i(t) \tag{3}$$

where $T_o(t)$ is the output or the response of the system (i.e., sensor temperature), τ is the time constant (s), and $T_i(t)$ is the input function (i.e., air temperature).

2.3. Time constant

The time constant is derived from concepts of conservation and energy transfer between the sensor and the surrounding environment (McGee, 1988). Assuming the thermocouple sensor geometry is best described as a cylindrical wire,

$$\tau = \frac{\rho_w C_w d^2}{\gamma k Nu} \tag{4}$$