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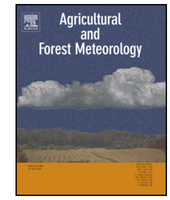

On the energy balance closure and net radiation in complex terrain

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ABSTRACT

In complex, sloping terrain, horizontal measurements of net radiation are not reflective of the radiative energy available for the conductive and convective heat exchange of the underlying surface. Using data from a grassland site on a mountain slope characterised by spatial heterogeneity in inclination and aspect, we tested the hypothesis that a correction of the horizontal net radiation measurements which accounts for the individual footprint contributions of the various surfaces to the measured sensible and latent heat eddy covariance fluxes will yield more realistic slope-parallel net radiation estimates compared to a correction based on the average inclination and aspect of the footprint. Our main result is that both approaches led to clear, but very similar improvements in the phase between available energy and the sum of the latent and sensible heat fluxes. As a consequence the variance in the sum of latent and sensible heat flux explained by available radiation improved by >10%, while energy balance closure improved only slightly. This is shown to be mainly due to the average inclination and aspect corresponding largely with the inclination and aspect of the main flux source area in combination with a limited sensitivity of the slope correction to small angular differences in, particularly, inclination and aspect. We conclude with a discussion of limitations of the present approach and future research directions.

1. Introduction

The widespread observation that the sum of the latent (λE) and sensible (H) heat exchange measured by the eddy covariance method systematically underestimates the available energy, i.e. net radiation (R_n) minus the energy storage in the system (S), by 10–40 % (Stoy et al., 2013), has been puzzling the micrometeorological community for several decades (Eq. 1):

$$R_n - S = \lambda E + H, \tag{1}$$

where we adopt a sign convention by which positive fluxes are directed towards the atmosphere and *vice versa*.

As the lack of energy balance closure violates the first law of thermodynamics and may be indicative of systematic measurement errors in the individual terms of Eq. (1), a large body of literature has accumulated on this topic. In a review, Foken (2008) concludes that errors of well-maintained and regularly calibrated net radiometers are unlikely to contribute significantly to the energy imbalance and that underestimations of S (see also Leuning et al., 2012) and in particular of λE and H (e.g. Eder et al., 2014) are more likely to cause the observed underestimation of the right-hand-side of Eq. (1).

In complex, sloping terrain, however, the additional problem arises that horizontally measured net radiation does not reflect the radiative energy experienced by the underlying, sloping surface. A common symptom of this mismatch is net or available radiation being out of phase with the sum of λE and H (Hammerle et al., 2007; Hiller et al., 2008; Serrano-Ortiz et al., 2015). In such a situation, net radiation either needs to be measured in a slope-parallel fashion (e.g. Matzinger et al., 2003; Serrano-Ortiz et al., 2015) or transferred into a slope-parallel framework by an appropriate mathematical transformation (Nie et al., 1992; Whiteman et al., 1989). Doing so is complicated by the mismatch in footprint between net radiation and eddy covariance flux measurements (Schmid, 1997), in particular if, as frequently the case under real-world conditions, the eddy covariance flux footprint is spatially heterogeneous in terms of inclination and aspect. In such a case, the correction of horizontal net radiation should actually be weighted by the individual contributions of the underlying surfaces of various inclinations and aspect to the total flux measured at the eddy covariance tower. So

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far, to the best of our knowledge, this has not been attempted and researchers instead have used average inclination and aspect of the slope in the correction (Hammerle et al., 2007; Hiller et al., 2008).

The objective of this study is thus to correct horizontally measured net radiation by weighting with the footprint contribution of the underlying surface and to compare this approach against the correction based on the average inclination and aspect of the eddy covariance flux footprint. The main hypothesis underlying this study is that at study sites characterised by spatial variability in inclination and aspect, the footprint-weighted correction will yield more realistic net radiation estimates. In order to test this assumption we conducted a study at a southwest facing grassland slope in the Northern Italian Alps characterised by a large spatial heterogeneity in terms of inclination and aspect.

2. Material and methods

2.1. Study site

The study site (46.68° N, 10.59° E) is situated at an elevation of around 1550 m a.s.l. on a southwest facing slope of the Venosta Valley in northern Italy (Fig. 1). Average (1980–2010) annual temperature amounts to 6.5 °C, annual precipitation to 550 mm. The study site is lightly grazed by cattle and sheep in spring and fall. During summer, plant growth is limited by low soil water contents. Vegetation is hence dominated by drought and grazing adapted grasses (*Festuca valesiaca* agg.), herbs (*Hieracium pilosella* agg.) and shrubs (*Juniperus communis* agg.). Soils are shallow leptosols and characterised by high sand and silt contents.

2.2. Eddy covariance and ancillary measurements

The net exchange of sensible and latent heat between the study site and the atmosphere was quantified using the eddy covariance (EC) method (Aubinet et al., 2000; Baldocchi et al., 1988). Measurements started on 4th June 2014 and continue as of this writing, here we report data until 30th September 2014. The three wind components and the speed of sound were measured with a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, USA) mounted 2 m vertically above a small flat spot. Water vapour (and carbon dioxide) mole densities were measured with an open-path infrared gas analyser (Li-7500, LiCor, USA), which was displaced by 0.1 m laterally and 0.2 m longitudinally compared to the sonic anemometer in order to minimize flux loss due to sensor separation and to avoid disturbance of the wind field. A data logger (CR3000, Campbell Scientific, USA) acquired the serial data from both instruments at 20 Hz using the SDM protocol and stored them to a 2 GB data card. The data logger was programmed to turn off the infrared gas analyser and sonic anemometer through a relay when the AGC-value of the infrared gas analyser exceeds 70% (clean background value of 50%) and/or the digital sonic status signal deviated from zero in order to save power during precipitation. The data logger would then check the AGC-value and the sonic status shortly before the start of each half-hour and recommence data acquisition and logging if signals have returned to normal values. Digital time lags between the sonic anemometer and the infrared gas analyser data streams due to signal processing were accounted for by the data logger program. Post-processing of these raw data was conducted using the free software EdiRe (University of Edinburgh, UK). Half-hourly average fluxes of latent and sensible heat and CO_2 were calculated as the covariance between the turbulent fluctuations of the vertical wind speed and the water vapour density and sonic temperature, respectively, after subtracting the time series arithmetic average and applying a planar fit rotation (Wilczak et al., 2001) to the wind data. Frequency response corrections accounting for both high- and low-pass filtering were applied following Moore (1986) and Aubinet et al. (2000) using a site-specific model cospectrum as in Wohlfahrt et al. (2005). The buoyancy flux was converted to the sensible heat flux according to Schotanus et al. (1983) and latent heat fluxes were corrected for the effects of density fluctuations based on Webb et al. (1980). No corrections were applied for the self-heating of the open-path infrared gas analyser, as these are known to be negligible during the warm season (Burba et al., 2008; Haslwanter et al., 2009), but we increased H, λE and CO_2 fluxes by 5% to account for sonic anemometer flow distortion due to transducer shadowing (Horst et al., 2015). The net exchange of sensible and latent heat and CO_2 was then calculated as the sum of the respective corrected eddy covariance and the storage flux, which was calculated as the vertically integrated rate of change of latent/sensible heat at the measurement height (> 95 % of all times less than $\pm 1\,W\,m^{-2}$ for energy fluxes and $\pm 0.5\,\mu mol\,m^{-2}\,s^{-1}$ for CO_2 fluxes).

Data were rejected when the stationarity or integral turbulence test exceeded 60% deviation (Foken and Wichura, 1996). Together with system shut-downs due to signal quality (see above), this resulted in a data coverage of 78% and 83% for H and λE during the study period, respectively.

Ancillary data measured by the same data logger at 30 s time intervals (100% data coverage during study period) and averaged to 30 min values included: air temperature and humidity at 2 m height above ground (HMP45C, Campbell Scientific, USA), incoming and reflected/outgoing short- and longwave radiation (CNR-1, Kipp & Zonen, the Netherlands; 10 % accuracy on daily totals), soil temperature (integral over the depth of 0-0.05 m; TCAV, Campbell Scientific, USA), soil moisture at 0.05 m soil depth (ML2x, Delta-T, UK), and soil heat flux at 0.05 m soil depth (two replicates, HFP01, Hukseflux, the Netherlands).

The soil heat flux through the soil surface was derived by accounting for the heat storage above the soil heat flux plates using measured soil temperature and soil water content and known soil bulk and particle density, as well as the fraction of soil organic matter following Sauer and Horton (2005).

Additional heat storage in the above-ground biomass and photosynthesis was accounted for according to Jacobs et al. (2008). The heat storage in the above-ground biomass (S_c) was calculated from the rate of change in surface temperature (T_{surf}), as measured with the net radiometer, times the mass of above-ground dry organic matter (m_o, 0.30 kg m^{-2}) and water (m_w, 0.38 kg m^{-2}), each multiplied with the corresponding specific heat capacities (C_o: 1920 and C_w: 4190 J kg^{-1} K^{-1}), i.e.

$$S_c = \frac{\Delta T_{surf}}{\Delta t}\left(C_w m_w + C_o m_o\right). \tag{2}$$

S_c ranged between $\pm 5\,W\,m^{-2}$ in more than 90% of all times. The heat storage in photosynthesis (S_p) was calculated based on estimated gross photosynthesis assuming that 0.5 J are required to fix one molecule CO_2 (Goudriaan and van Laar, 1994). Gross photosynthesis was inferred from the daytime net ecosystem CO_2 exchange by adding an estimate of ecosystem respiration, which in turn was derived from nighttime measurements as detailed in Wohlfahrt et al. (2008b) and Wohlfahrt and Gu (2015). In more than 90% of all times, S_p amounted to less than $10\,W\,m^{-2}$.

All data are reported with reference to the Central European Time (CET).

2.3. Footprint modelling

The source area of the eddy covariance flux measurements was calculated based on the 2-dimensional footprint model by Detto et al. (2006), which is an extension of the 1-dimensional (cross-wind integrated) footprint model by Hsieh et al. (2000). The latter