Agricultural and Forest Meteorology 211–212 (2015) 115–127

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Secondary circulations at a solitary forest surrounded by semi-arid shrubland and their impact on eddy-covariance measurements

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ARTICLE INFO

Article history:
Received 4 December 2014
Received in revised form 26 May 2015
Accepted 1 June 2015
Available online 25 June 2015

Keywords:
Eddy covariance
Large-eddy simulation
Lidar
Ogive analysis
Secondary circulation

ABSTRACT

The Yatir forest in Israel is a solitary forest at the dry timberline that is surrounded by semi-arid shrubland. Due to its low albedo and its high surface roughness, the forest has a strong impact on the surface energy budget, and is supposed to induce a secondary circulation, which was assessed using eddy-covariance (EC) and Doppler lidar measurements and large-eddy simulation (LES). The buoyancy fluxes were 220–290 W m^{-2} higher above the forest, and the scale of the forest relative to the boundary-layer height is ideal for generating a secondary circulation, as confirmed by a LES run without background wind. However, usually a relatively high background wind (6 m s^{-1}) prevails at the site. Thus, with the Doppler lidar a persistent updraft above the forest was detected only on 5 of the 16 measurement days. Nevertheless, the secondary circulation and convective coherent structures caused low-frequency flux contributions in the mixed-layer *w* spectra, the surface layer *u* and *w* spectra and in the surface-layer momentum fluxes. According to the ogive functions from the tower data and a control volume approach using the LES, such low-frequency contributions with timescales >30 min were a major reason the non-closure of the energy balance at the desert site. In the roughness sublayer above the forest, these large structures were broken up into smaller eddies and the energy balance was closed.

1. Introduction

The convective atmospheric boundary layer is conceptually divided into a surface layer and a mixed layer or outer layer (Driedonks and Tennekes, 1984). The turbulence of the homogeneous surface layer under stationary convective conditions obeys Monin–Obukhov similarity theory. In addition, large convective coherent structures that scale with the height of the atmospheric boundary layer influence the horizontal wind component (Kaimal, 1978; Højstrup, 1981). They are often called ‘inactive motions’ because according to Townsend (1961) and Bradshaw (1967) they are imprints of large turbulent fluctuations originating from the outer layer and do not contribute to shear stress. The convective coherent structures are thermals (Wilczak and Tillman, 1980; Williams and Hacker, 1993), open cells (Kropfli and Hildebrand, 1980; Träumner et al., 2014) or, in case of background wind, as horizontal rolls (Etling and Brown, 1993; Drobinski et al., 1998; Maronga and Raasch, 2013) and typically have horizontal length scales of 1.5 times the boundary-layer height (Kaimal et al., 1976; Caughey and Palmer, 1979; Liu et al., 2011). However, homogeneous field conditions can rarely be met in reality, which complicates the application of universal scaling rules and the interpretation of boundary-layer measurements. Differences in surface roughness, temperature or moisture are supposed to create internal boundary layers (Garratt, 1990; Strunin et al., 2004), to induce advection on the surface-layer or boundary-layer scale (Raupach and Finnigan, 1995; Higgins et al., 2013) and, if the differences in surface properties are strong enough and if the surface patches are large enough, to induce secondary circulations (Mahfouf et al., 1987; Dalu and Pielke, 1993; Courault et al., 2007; van Heerwaarden and Vilà-Guerau de Arellano, 2008; Garcia-Carreras et al., 2010; Sühring and Raasch, 2013; Dixon et al., 2013; Kang and Lenschow, 2014; van Heerwaarden et al., 2014).

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http://dx.doi.org/10.1016/j.agrformet.2015.06.001
0168-1923/

Large-scale boundary-layer structures also have an effect on surface flux measurements conducted with the eddy covariance technique (Foken, 2008; Foken et al., 2011). The eddy-covariance (EC) method is very attractive for determining land-atmosphere exchange of energy and traces gases, since it does not disturb the ecosystem under investigation and the flux measurement operates on the ecosystem scale, i.e. it is representative of a larger area (Schmid, 1994; Baldocchi, 2003). However, this method generally does not close the energy balance at the earth's surface, which is called the energy balance closure problem (Foken, 2008). Accordingly, the energy balance ratio R, which is the sum of sensible heat flux Q_H and latent heat flux Q_E divided by net radiation $-Q_S{}^*$ minus the ground heat flux Q_G,

$$R = \frac{Q_H + Q_E}{-Q_S{}^* - Q_G}, \tag{1}$$

is usually smaller than unity. Multi-site analyses across different ecosystems have shown that energy balance ratios usually range between 0.7 and 0.9 (Wilson et al., 2002; Hendricks-Franssen et al., 2010; Stoy et al., 2013).

A potential reason for this is the non-consideration of fluxes carried by (i) turbulent structures with timescales larger than the averaging time of the EC system (Sakai et al., 2001; Turnipseed et al., 2002; Foken et al., 2006; Charuchittipan et al., 2014) or by (ii) secondary circulations that are bound to surface heterogeneities and do not move in space (Lee and Black, 1993; Mahrt, 1998; Hiyama et al., 2007). There are indications that the non-closure of the energy balance is related to the heterogeneity of the surrounding landscape (Mauder et al., 2007a; Panin and Bernhofer, 2008; Stoy et al., 2013), but experimental evidence that secondary circulations are an important transport mechanism in the surface layer is still lacking.

In this study, we aim to investigate the structure of the convective boundary layer above a well-defined surface heterogeneity. The Yatir forest in Israel is a planted pine forest with a scale of approximately 6–10 km, located in a semi-arid region at the dry timberline at the northern border of the Negev desert. Due to its low albedo and its increased surface roughness as compared to the semi-arid desert, the forest generates higher turbulent heat fluxes than the adjacent desert (Rotenberg and Yakir, 2011). We hypothesize that the resulting spatial differences in surface buoyancy flux,

$$Q_B = Q_H \left(1 + 0.61 T \frac{c_p Q_E}{\lambda Q_H}\right), \tag{2}$$

where T is the temperature, c_p is specific heat of air at constant pressure and λ is the heat of vaporization (Schotanus et al., 1983; Charuchittipan et al., 2014), should drive a secondary circulation between the forest and the desert. For this reason, it will be investigated whether Yatir forest is large enough and whether the surface heat flux differences are strong enough to modify the convective boundary-layer dynamics and to induce a secondary circulation. Scaling approaches, ground-based remote sensing measurements, high-frequency 3d-wind measurements and large-eddy simulation (LES) will be used for this study. In particular, the role of secondary circulations for the measured surface energy balances at the forest and the desert site will be investigated. It is intended to provide evidence why the turbulent heat fluxes are likely to be underestimated by the EC method. For this purpose, wind spectra and ogive functions will be calculated and the LES model will be used to identify the missing flux components by considering the flux budget equation of virtual control volumes.

2. Methods

2.1. Research site

The measurements (Fig. 1) were taken at Yatir pine forest (31°20′43.1″N, 35°3′6.7″ E, 660 m a.s.l.) and in the nearby semi-arid shrub land (31°19′6.5″N, 34°58′54.84″E, 461 m a.s.l.). The site lies in the transition zone between the Mediterranean climate and the semiarid climate. The mean annual precipitation is 285 mm with a distinct dry summer period. The measurement campaign lasted from 21 August to 11 September 2013. As such, it took place more than 6 months after the last rain event in the area.

The Yatir forest is dominated by *Pinus halpensis* trees of 11 m height that were planted mostly from 1964 to 1969 and cover an area of about 2800 ha (Grünzweig et al., 2003; Rotenberg and Yakir, 2011). The surrounding area has been under grazing for at least several decades and is sparsely covered with shrubs and herbaceous annuals and perennials. Since the measurements were conducted at the end of the dry season, the major part of the semi-arid shrub-

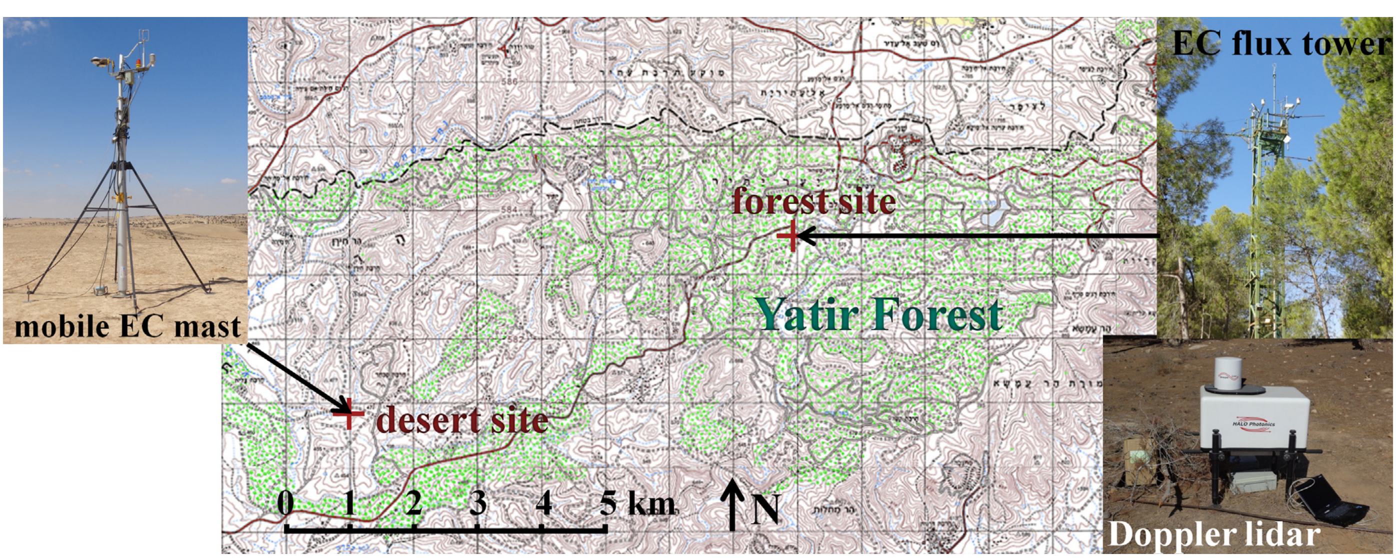

Fig. 1. Topographic map of the Yatir forest showing the locations of the measurement devices at the desert site and the forest site. Please note that there is no forest south and west of the desert site at present.