Remote Sensing of Environment 124 (2012) 742–755

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Characterizing spatial representativeness of flux tower eddy-covariance measurements across the Canadian Carbon Program Network using remote sensing and footprint analysis

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ARTICLE INFO

Article history:
Received 27 May 2011
Received in revised form 29 May 2012
Accepted 3 June 2012
Available online 21 July 2012

Keywords:
Fluxnet
Footprint climatology
Spatial representativeness
Eddy-covariance
Remote sensing

ABSTRACT

We describe a pragmatic approach for evaluating the spatial representativeness of flux tower measurements based on footprint climatology modeling analyses of land cover and remotely sensed vegetation indices. The approach was applied to the twelve flux sites of the Canadian Carbon Program (CCP) that include grassland, wetland, and temperate and boreal forests across an east–west continental gradient. The spatial variation within the footprint area was evaluated by examining the spatial structure of Normalized Difference Vegetation Index (NDVI) and land cover using geostatistical analyses of frequency distribution, variogram and window size. The results show that at most sites (i) the percentages of the target vegetation functional type (dominant land cover) observed by the CCP towers were higher than 60%; (ii) to some extent, most of the CCP sites presented anisotropically distributed patterns of NDVI in the 90% annual footprint climatology area; and (iii) the land surface heterogeneity within the flux footprint area differed among sites. Overall, the forest sites had larger fine-scale spatial variation than the grassland and wetland sites. The coniferous boreal forest sites had greater spatial variability than the two wetland sites and a coniferous temperate forest site. We conclude that the combination of footprint modeling, semivariogram and window size techniques, together with moderate spatial resolution remotely-sensed image data, is a pragmatic approach for assessing the spatial representativeness of flux tower measurements.

1. Introduction

The eddy covariance (EC) technique is commonly used to measure CO_2, water vapor and energy exchange between the atmosphere and terrestrial ecosystems (Baldocchi, 2008). The use of the EC technique to estimate surface exchange is based on the assumption that the contributing area of the fluxes (i.e. footprint area) is topographically flat and the vegetation extends uniformly (Baldocchi, 2003, 2008; Finnigan et al., 2003; Foken & Wichura, 1996). In reality however, there are few such ideal sites, with spatial heterogeneity generally causing problems in data quality, data analysis, and proper interpretation of EC-data (Sogachev et al. 2004). These problems can be addressed if the spatial representativeness of the measurements is known.

Individual towers provide information on the gas exchange between vegetation and the atmosphere which is assumed to be characteristic for a given ecosystem of interest (a target ecosystem) (Schmid & Lloyd, 1999). On this basis, networks of EC systems have been set up at biome, national, continental, and global scales based loosely

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doi:10.1016/j.rse.2012.06.007

on the idea that individual nodes are representative of larger ecosystems (Baldocchi, 2008). However, utilization and application of EC measurements (especially for spatial up-scaling to landscape and regional scales) can be problematic due to difficulties/uncertainties in understanding/interpreting the long-term EC measurements (Chen et al., 2009a; Gockede et al., 2004; Rebmann et al., 2005). The spatial variation within the EC flux footprint area needs to be assessed prior to the data from these networks being combined with remote sensing data and/or ecosystem models to determine spatial and temporal variability of CO_2 exchanges over heterogeneous landscapes that have undergone some prior disturbance (e.g., land management, extreme weather, insect infestation, fire, etc.), or that contain different stand ages, species types (e.g., Heinsch et al., 2006).

Footprint models have been developed to estimate the probability of fluxes originated from a particular place surrounding the tower. The spatial variability of the source strength is usually controlled by the surface vegetation characteristics and soil conditions. It is assumed that the spatial variability of vegetation density is significantly correlated with that of the source flux strength (Kim et al., 2006). The combination of footprint modeling and remotely-sensed high-resolution image data is then proposed to characterize the heterogeneity over the EC flux footprint area (Chen et al., 2009a; Kim et al., 2006).

In this paper, we present a method to combine remotely sensed vegetation indices, a widely used land cover map, and a footprint model to characterize the source of the EC fluxes. This methodology was applied to the 12 main study sites of the Canadian Carbon Program (CCP) network (previous Fluxnet Canada Research Network). The footprint climatology, i.e. footprint estimates for long-term EC measurements, was calculated using the Simple Analytical Footprint model on Eulerian coordinates (SAFE-F, Chen et al., 2009a). A vegetation index (NDVI: Normalized Difference Vegetation Index) is generally related to green vegetation cover or vegetation canopy density. NDVI is also considered to be a relative and indirect indicator of photosynthetic capacity and is sometimes corrected with biophysical parameters such as green leaf biomass (e.g., Govind et al., 2009; Myneni et al., 1995; Sellers, 1985) and the fraction of green vegetation cover (Myneni et al., 1995). The NDVI used as a surrogate of the land-surface flux was derived from Landsat Thematic Mapper (TM) or Enhanced TM (ETM+) imagery data. The spatial variation within the footprint climatology area was evaluated by examining the spatial structure of the vegetation index and land cover using geostatistical measures, including the frequency distribution, variogram and window-size analyses.

2. Methods and data

2.1. Site characteristics

We selected 12 main flux tower sites of the CCP distributed along an east–west continental transect in Canada (Fig. 1). These sites cover four major biome types (grassland, wetland and both temperate and boreal forests) and six ecoregions (from west to east: Pacific maritime, prairies, boreal plains, boreal shield, mixed wood plains and Atlantic maritime). Site and EC flux tower characteristics are summarized in Table 1 (http://www.fluxnet-canada.ca).

2.2. Footprint and footprint climatology modeling

The footprint probability distribution function (PDF) of the measured fluxes can be estimated with footprint models (e.g., Schmid, 1994; Kljun et al., 2004; Chen et al., 2009a). However, the complexity and large computational demand of some models restricts their practical applicability. For multi-site EC datasets, it is advantageous to use a somewhat simplified footprint model that still retains the ability to discern spatial footprints. In this study we used the Simple Analytical Footprint model on Eulerian coordinates for scalar Flux (SAFE-F, Chen et al., 2009a) to compute the footprint PDF. This analytical footprint model takes into account atmospheric stability and uses the wind velocity power law above the canopy, allowing it to be applicable to a wide range of atmospheric conditions.

The SAFE-F model input includes the EC sensor height (h_m), canopy height (h_c), roughness length (z_0), friction velocity (u_*), u_* threshold for EC flux calculation (u_*^{th}), wind direction (WD), wind speed (u), standard deviation of lateral wind speed (σ_v), and sensible and latent heat fluxes measured at the EC sensor height. The input meteorological variables were measured in 2006, which was generally considered a normal weather year over most of the sites. These data were acquired from the CCP database (http://www.fluxnet-canada.ca/). Missing flux and meteorological data were filled using the gap-filling method of Chen et al. (2009b). The input land surface parameters h_m and h_c were taken from the literature as shown in Table 1 and z_0 is approximated as 10% of h_c (Raupach, 1994).

The EC flux community has recognized that the EC technique often underestimates nighttime net ecosystem exchange (NEE) during periods when turbulent mixing is insufficient (e.g. Black et al., 2000; Goulden et al., 1996; Jarvis et al., 1997). For a practical solution, these data obtained during calm, nocturnal periods are filtered using friction velocity as an indicator by many research groups. Similarly, the periods with low turbulence should be excluded in footprint calculation. The determination of an adequate u_*^{th} is crucial, however at present; there is no commonly accepted method to determine the adequate u_*^{th}. In the literature, researchers often find the u_*^{th} by visually examining the scatter plot of nighttime fluxes versus u_*: the threshold is located where the flux begins to level off as u_* increases. Because the EC fluxes measured during nighttime often appear to be rather noisy in the NEE versus u_* scatter plot, it is common that no clear patterns can be recognized visually (Gu et al., 2005). Even when there are easily identifiable patterns, the selection of u_*^{th} depends on the operator's subjectivity. To overcome such problems, different alternative heuristic methods have been proposed to automatically determine the appropriate u_*^{th} (Gu et al., 2005; Reichstein et al., 2003, 2005), but the uncertainty of the determination of u_*^{th} is still considerable. There is no basis to think that u_*^{th} is constant over time. It may well depend on leaf area distribution, stem density, canopy height, as well as meteorological conditions and terrain characteristics. Consequently, employing a single u_*^{th} all the time may also introduce biases (Papale et al., 2006). For all the 12 CCP flux tower sites, however, the u_*^{th} value is determined by each tower operator and treated as a constant over time.

There is a need to minimize methodological uncertainties introduced by the different u_* threshold selection procedures for the purpose of site intercomparisons. To determine the time-varying u_*^{th} for footprint calculation using the SEAF-F model, we applied a standardized method proposed by Papale et al. (2006) to all the 12 CCP sites. Briefly, the annual raw dataset was first divided into four seasons (January–March, April–June, July–September and October–December) and the each season's dataset was further split into six temperature classes with equal sample size: the threshold for each temperature class was only accepted if u_* is not or only weakly correlated with temperature ($|r|<0.4$), and the final threshold for each season was defined as the median of the thresholds of the (up to) six temperature classes. The standardized time-varying u_*^{th} values which were used in the SEAF-F model for individual CCP sites are different from those time-constant values determined by the tower operators (Table 1).

The model was run at half-hourly time steps at a grid size of 30×30 m (consistent with the Landsat spatial resolution) covering the domain area (6×6 km) centered on the towers. The half-hourly footprint PDFs were rotated along the wind direction and then accumulated to yield monthly, seasonal or annual values, of the footprint climatology.

The cumulative percentage footprint was calculated by: (i) sorting the footprint climatology in a descending order; and (ii) accumulating its value from the largest to the smallest. The detailed description