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Numerical study of the interplay between thermo-topographic slope flow and synoptic flow on canopy transport processes

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ABSTRACT

Canopy flow resulting from interaction between thermo-topographic slope flow and large-scale synoptic flow is very complicated and has been poorly understood. We apply a Reynolds-averaged Navier-Stokes (RANS) turbulence model to investigate how the interactions between local flow and synoptic winds affect CO_2 movement in the canopy layer at the Renon site in the Italian Alps. Since the RANS simulations are compared to the data measured by multiple-tower experiments conducted during CarboEurope-IP advection campaigns (ADVEX) at Renon, our study can be viewed as a case study of a relatively common wooded slope. The thermal condition in the canopy is directly related to the canopy morphology: the dense canopy at our site causes stronger cooling but limits vertical exchange of heat flux, resulting in weak temperature inversion in the deep canopy. Under conditions with no synoptic wind, local flow leads to CO_2 build-up mainly at downslope locations and no recirculation is formed. Recirculation that holds high CO_2 mole fraction in the canopy is developed only under the condition that local slope wind is enhanced by northerly synoptic winds. No recirculation forms when southerly synoptic wind direction is opposite to the local wind direction, in which case CO_2 is quite well mixed. This numerical study approach brings to light a better understanding of the CO_2 closure problem: the measured net ecosystem exchange of CO_2 is more likely to be underestimated in local non-synoptic slope flow and local synoptic-enhanced slope flow regimes at Renon. However, small-scale heterogeneity in canopy structure, variability in the CO_2 source from soil and higher-resolution and larger-scale topography still challenge the application of this numerical approach in the FLUXNET community.

1. Introduction

Accurate quantification of net ecosystem-atmosphere exchanges of mass and energy is a fundamental and critical step in reducing the uncertainty of how the large-scale climate change interacts with local ecosystems. The eddy covariance (EC) technique has proven to be a useful approach to quantify net ecosystem carbon exchange in the daytime when strong turbulent mixing occurs. In the night, nocturnal flux measurements ignore advection fluxes that can be of the same order as the eddy flux itself when flux sites are located in complex terrain (Massman and Lee, 2002; Feigenwinter et al., 2004, 2008, 2010a, 2010b; Aubinet et al., 2003; Aubinet, 2008; Aubinet et al., 2010; Aubinet and Feigenwinter, 2010; Finnigan, 2008; Goulden et al., 2006; Montagnani et al., 2009; Yi et al., 2000). The three-dimensional (3D) details of air movement, CO_2 transport, and temperature variation around the instrumented tower cannot be fully ascertained using EC measurements at a point, particularly in complex terrain. Massman and Lee (2002) stated that understanding of 2D and 3D flows and their role in micrometeorological flux observation is of great importance to any site; however, the problem of 2D and 3D flows is most difficult to evaluate at sites on non-flat terrain.

The errors of single tower measurements are more serious during calm nights in forested complex terrain, which is subject to the mechanisms of nocturnal canopy flow, *e.g.* turbulent ramps, gravity waves, intermittent turbulence, land, sea or lake breezes and drainage flows (Aubinet, 2008). The canopy flow resulting from interactions of site-specific topography and vegetation causes significant complexity in CO_2 transport that varies from case to case. At night periods, the ecosystem behaves as a CO_2 source because soil and above ground vegetation respiration are not offset by photosynthesis. CO_2 tends to accumulate near the ground due to surface

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layer stratification particularly in conditions of a super-stable layer within the canopy (Yi et al., 2005), resulting in strong negative vertical CO_2 gradients (Yi et al., 2008; Araújo et al., 2008). The negative vertical gradient of CO_2 with subsiding background wind contributes to positive vertical advection of CO_2 transport. Along the slope, much higher CO_2 concentration is commonly observed at lower altitude (slope and valley) than at higher altitude (plateau) (Araújo et al., 2008). The positive CO_2 gradient from high altitude to low altitude, along with drainage flow, results in a positive contribution to horizontal advection. Although positive advection in both vertical and horizontal is very common at night in sloped terrain, some observations reveal the complexity of the advection processes. For instance, airflow with low CO_2 concentration entrains from the top of the canopy to the surface contributing to a negative horizontal CO_2 gradient along the drainage flow direction and resulting in negative horizontal advection (Aubinet et al., 2003; Aubinet, 2008). Local terrain and vegetation effects can cause positive vertical velocity at night, resulting in negative vertical advection (Turnipseed et al., 2003). The vertical gradient of CO_2 distribution was found to be large on the upper slope but quite uniform on the lower slope (Reiners and Anderson, 1968; Araújo et al., 2008; Aubinet, 2008), implying smaller vertical advection in the CO_2-pooled valley than on the upper slope. All these observations have demonstrated the complexity and 3D effects of the advection on eddy flux measurements.

The eddy flux communities have made great efforts to conduct experiments with multiple-tower and multiple-level measurement systems to capture the 3D characteristics of wind fields and CO_2 movement to study the advection issues, such as the CarboEurope-IP advection campaigns (ADVEX) (Feigenwinter et al., 2008), advection measurements conducted at the AmeriFlux Niwot Ridge site (Sun et al., 2007; Yi et al., 2008) and tropical Amazon Rainforest (Tóta et al., 2012; Santana et al., 2017). The measured advection fluxes are of similar magnitudes as the turbulent fluxes during calm nights, and vary from site to site (Feigenwinter et al., 2008; Yi et al., 2008). The important feature is that the advection contribution is closely correlated to local and synoptic meteorological conditions. Local orographic flow is most likely to occur within the canopy, while synoptic wind is dominant above the canopy. However, synoptic flows can penetrate into the open canopy and interact with orographic flow (Sun et al., 2007). The process of interaction includes synoptic winds that enhance, attenuate, or even alter the direction of the orographic wind, depending on the direction and strength of prevailing synoptic winds (Feigenwinter et al., 2010a). Accordingly, the modified orographic flows have direct influence on CO_2 pooling or mixing, and hence on measured CO_2 flux.

Although the direct advection measurements provide insights into the wind fields and CO_2 transport at the research sites, the conclusions drawn may not be applicable to other FLUXNET sites subject to the conditions of local terrain and vegetation and large-scale synoptic conditions. In addition, the representativeness of the multiple-tower measurements is very sensitive to the tower setup and methodology used to derive the fluxes from measurements (Aubinet et al., 2010; Aubinet and Feigenwinter, 2010; Montagnani et al., 2010; Vickers and Mahrt, 2006). How can we take advantage of the single tower measurements found at most FLUXNET sites to understand 'site-specific' CO_2 transport processes? In this study, we aim to numerically resolve the 3D spatial variability of airflow and CO_2 transport initialized by measurements on one tower, but tested by multiple-tower experiments conducted during the ADVEX campaign at the Renon (RE) site in the Italian Alps. The airflows are simulated under various synoptic conditions to explore the interactions between local orographic flow and synoptic-scale winds, and related CO_2 processes. We hypothesize that (1) the interactive wind as a result of the synoptic and local slope winds varies with synoptic-scale weather patterns, (2) recirculation forms when synoptic and local winds enhance each other, and (3) canopy density along with the interactive winds leads to uneven heat and CO_2 transport: the cool air and CO_2 tend to pool in the recirculation zone and leeward slope (Fig. A1). We first describe the characteristics of terrain, vegetation and measurement set-up in Section 2, then we present the numerical method in Section 3 followed by results and discussions in Section 4. The conclusions are drawn in Section 5.

2. Site and data description

This numerical study is conducted based on the extensive measurements performed during the ADVEX campaign at the Renon-Selva Verde study site (RE, 46°25′ N, 11°17′ E,). RE is situated at about 1735 m above sea level in the Italian Alps, 12200 m North-Northeast of Bolzano. The Digital Elevation Model (DEM) of the 2000 m × 2000 m area around the RE is shown in Fig. 1 (labeled as D1). The topography of the site is characterized by alpine conditions with a main slope of about 11° that is locally oriented towards southeast in a mountain range having a principal North-South sloping direction. The vegetation at the site is characterized by a coniferous forest with gaps between groups of older and younger trees. The forest species are dominated by *Picea. abies* (85%), *Pinus cembra* (12%) and *Larix decidua* (3%), with a mean leaf area index (LAI) of 5.1 and maximal canopy height of 29–30 m in the 240 × 240 m research area (D2 in Fig. 1). The vegetation structure varies across the towers. A field survey in October 2009 classified the vegetation in D2 into three categories (Fig. 2): (1) Sparse forest in grassland, (2) Forest edge dominated by re-growth forest with sparse older trees, and (3) Mature forest.

The meteorological conditions at RE are dominated by the 'Tramontana' winds from the north or northwest (northerlies), typically in winter and occasionally in summer. Winds from the south (southerlies) tend to appear whenever there is a low-pressure system located over the Western Mediterranean area. Upslope (anabatic) winds during the day and down-slope (katabatic) winds during the night characterize the local (orographic) slope wind system.

An extensive measurement dataset (half-hourly averaged) was collected from the ADVEX campaign during May 1st to September 15th 2005. The ADVEX setup consisted of four external towers (A–D) and a permanent central tower (M) (Fig. A2). Each external tower was equipped for measurements of CO_2, H_2O, temperature, and wind vectors at heights of 1.5, 6, 12, and 30 m above ground level. An additional wind velocity measurement was made at 41.5 m on tower C. Measurement levels at tower M were 1.5, 6, 12, and 32m. A more detailed description of the site, measurement methods, and data processing can be found in Feigenwinter et al. (2008) and Montagnani et al. (2009).

3. Method

3.1. Conservation of mass and momentum

In configuring the numerical model, the flow is assumed to be steady state and the Boussinesq approximation is applied. The Navier-Stokes momentum and mass balance equations are applied to the canopy sub-layer with thermal stratification (Yi et al., 2005), which can be written as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad (1)$$

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P_*}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) - g_i \beta \left(\bar{\theta} - \theta_\infty\right) - F_{Di}, \quad (2)$$

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