15.A1 STEERING MECHANISMS OF A PERSISTENT SLOPE WIND SYSTEM ON PLOT-SCALE VERTICAL AND HORIZONTAL TRANSPORT OF CO_2 IN AND ABOVE AN ALPINE FOREST

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1. INTRODUCTION

Forests play an important role in the continental, regional and local carbon budget, because they are considered as the main terrestrial sink for CO_2. Within the global FLUXNET flux tower network, the eddy covariance technique has become the most important method for measuring the CO_2-exchange between forests and the atmosphere. However, many of these flux towers are situated in complex terrain and mountainous regions, and therefore subject to significant errors (Massman and Lee, 2002). A main source of error are terrain-induced flows, like e.g. nocturnal drainage flows. Terrain-induced flows result from multi-scale interactions between land surface and the overlaying atmosphere (Mahrt et al., 2001) and directly affect the land-atmosphere exchange of momentum, heat and scalars.

In this paper we analyze how the horizontal and vertical CO_2 transport is governed by a persistent slope wind system under different meteorological and synoptic conditions at the CarboEurope flux site in Renon/Ritten, Italian Alps, and the impact of the non-turbulent advective fluxes on net ecosystem exchange (*NEE*) for these situations is investigated.

2. SITE AND EXPERIMENTAL SETUP

The Renon/Ritten site is situated some 12 kms north of Bolzano at 1735 m a.s.l. on a south exposed steep (11°) forested slope in the Italian Alps. The main species is Norway Spruce (*Picea abies*) with a mean canopy height of 25 m. More details about the site can be found in Marcolla et al. (2005).

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Extensive measurements of the 3D wind vector and temperature with a high temporal and spatial resolution were made from 5 May to 15 September 2005 in the frame of the CarboEurope advection experiment ADVEX. Four additional towers of 30 m height were installed in about 60 m diagonal distance of the central flux tower to form a 3D cube control volume. Wind components *u, v, w,* and temperature *T* were measured at 4 levels (1.5, 6, 12 and 30 m) at each tower by ultrasonic anemometers at 10 Hz. In addition, CO_2 and H_2O concentrations were measured at the same locations every 160 s by two multi valve systems (MVS) each connected to a Li-6262 Infrared Gas Analyzer (IRGA). Fig. 1 shows the topography and the location of the towers. For further details about the experimental setup and instrumentation refer to Feigenwinter et al. (2008).

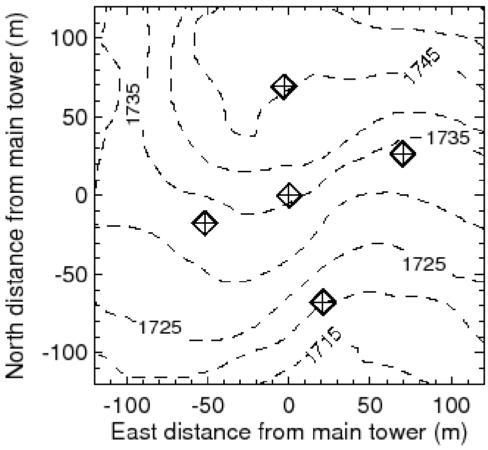

Fig. 1: Tower locations and topography. ADVEX towers are located around the main tower in the center.

3. SPATIAL INTEGRATION OF MEASUREMENTS

A modified linear interpolation scheme was used to derive vertical profiles from the measured CO_2 concentrations and the horizontal wind components at the four levels of each tower. Each level of these vertical profiles was bilinearly interpolated in a 5 m x 5 m grid between the four towers to obtain a "data cube" with CO_2 concentrations and horizontal wind components u and v (corresponding to *east (x)* and *north (y)* directions) for each grid point. From this data set storage change (F_S), vertical (F_{VA}) and horizontal (F_{HA}) advection was calculated according to

$$F_s = \frac{1}{V_m}\frac{z_r}{T}\frac{1}{4}\sum_i \left(\left\langle \overline{c_i}^T \left(\tfrac{T}{2}\right) \right\rangle - \left\langle \overline{c_i}^T \left(-\tfrac{T}{2}\right) \right\rangle \right)$$

$$F_{VA} = \frac{1}{V_m}\frac{1}{4}\sum_i \overline{w_i}(z_r)\left(\overline{c_i}(z_r) - \left\langle \overline{c_i} \right\rangle\right) \qquad \text{, Eq. (1)}$$

$$F_{HA} = \frac{1}{V_m}\frac{\Delta z}{N}\sum_{nx,ny,nz}\left(\bar{u}\frac{\Delta \bar{c}}{\Delta x}(x_j, y_k, z_l) + \bar{v}\frac{\Delta \bar{c}}{\Delta y}(x_j, y_k, z_l) \right)$$

where $\langle \bar{c} \rangle$ denotes the mean CO_2 concentration in the control volume under consideration, T refers to the time of one averaging period (usually 1 hour), and $\overline{w}(z_r)$ represents the mean vertical wind component at the reference height z_r, computed by the planar fit tilt correction algorithm after Wilczack et al. (2001). Index i refers to the four ADVEX towers, indices j, k, l refer to the x, y, z coordinates of the gridpoints, N is the number of grid points in the x-y plane, $\Delta c/\Delta x$ and $\Delta c/\Delta y$ are the CO_2 concentration gradients in x and y direction at the respective grid point, and Δz is the vertical thickness of a layer as defined by the resolution of the vertical interpolation scheme. According to Eq. (1), the total storage F_S and the total F_{VA} are the respective average of the four ADVEX towers, and total F_{HA} is the average of the vertically integrated F_{HA} at every grid point in the x-y plane.

If these fluxes are considered to be representative for the control volume, net ecosystem exchange *NEE* may be computed as

$$NEE = F_S + F_C + F_{VA} + F_{HA} \,. \qquad \text{Eq. (2)}$$

4. CO_2 TRANSPORT UNDER DIFFERENT METEOROLOGICAL CONDITIONS

Though in complex terrain, a persistent slope wind system with downslope winds during the night and upslope winds during the day established for most of the time (70 %) at the site during the measurement campaign. This local slope wind system was sometimes superimposed by two different large scale synoptic situations, the "Tramontana" and the "Southerlies" (about 15% each). A common feature of all three situations is the positive CO_2-concentration gradient in downslope direction during nighttime, probably resulting from source heterogeneities due to landuse change. This generally results in a positive value for F_{HA} and thus an additional source term if accounted for in *NEE*. In the following the three situations are analyzed in detail.

4.1 *Local slope wind system*

Fig. 2 shows the situation for local conditions during nighttime (top) and daytime (bottom). The direction of subcanopy flow is

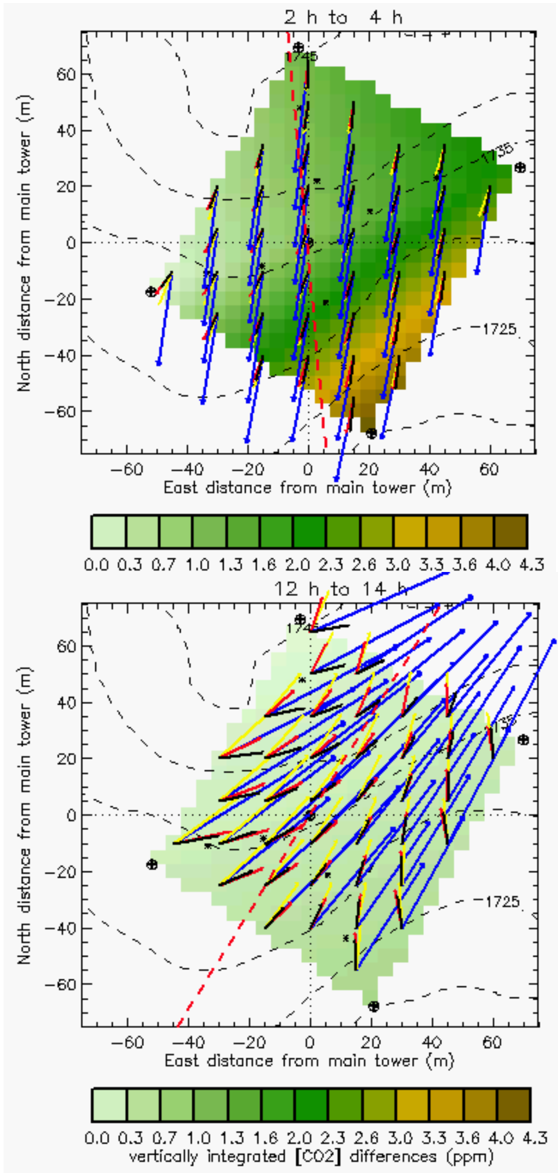

Fig. 2: Flow patterns and CO_2 concentration distribution (vertically integrated at gridpoints) in the control volume for local conditions during nighttime (top) and daytime (bottom). Black, red, yellow and blue arrows refer to wind vectors at levels 1.5, 6, 12 and 30 m a.g.l., respectively. A wind speed of 1 m s^{-1} is scaled with 25 m on xy-axis.

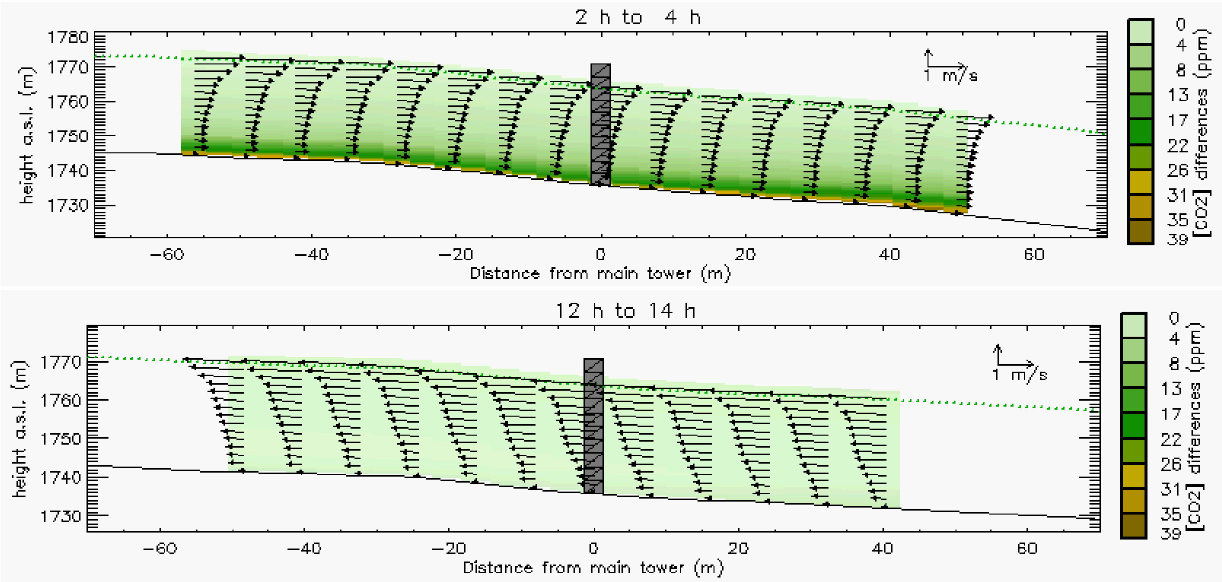

Fig. 3: Slice through the control volume along the red dashed lines in fig. 2 during nighttime (top) and daytime (bottom) under local conditions. The dotted green line refers to canopy height.

strongly influenced by the topography in the immediate vicinity of the towers, while the wind direction above canopy rather follows the large scale topography. This has an important impact on the total amount of F_{HA}. According to Eq. (1), F_{HA} depends on the angle between the direction of the concentration gradient and the wind vector in the respective vertical layer. This is accounted for by applying the presented method of calculation.

CO_2 accumulates close to the forest floor during nighttime, as shown in fig. 3 (top). The vertical CO_2 concentration gradient is largest in the lower trunk space and the largest mean concentrations are observed in the downslope region of the main tower. This results in a mean maximum nighttime value of about 10 μmol m^{-2} s^{-1} for F_{HA}, notably with large scatter. During daytime the air in the control volume is well mixed and concentration differences disappear nearly completely (fig. 3 bottom).

4.1 Tramontana

The “Tramontana”, a persistent (2-3 days) strong wind from the north, amplifies the

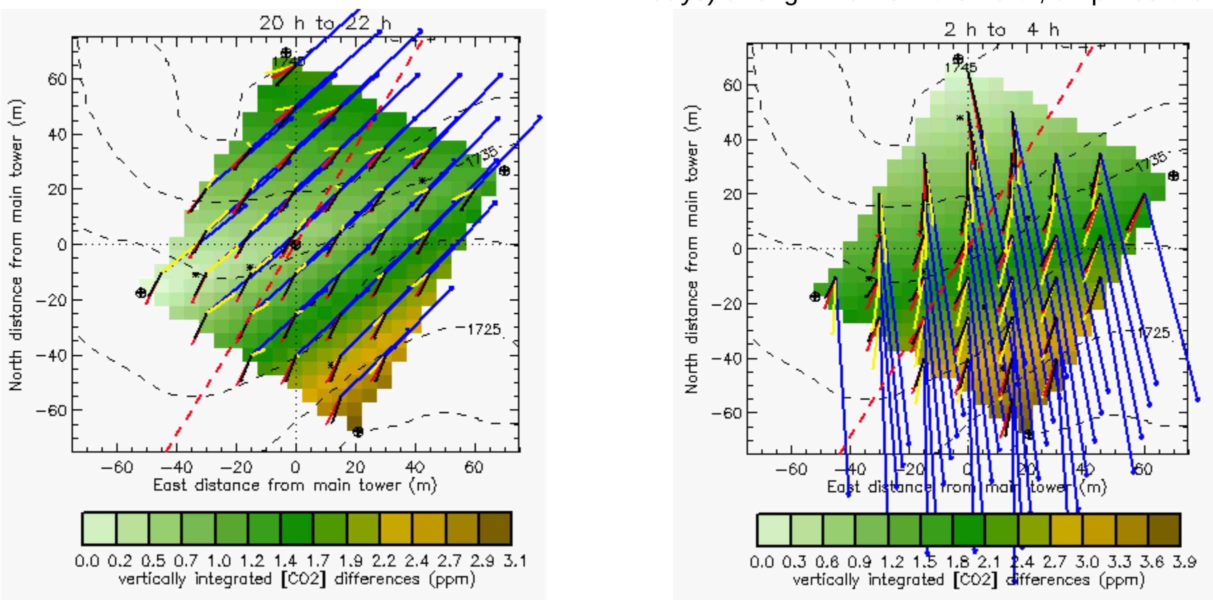

Fig. 4: Same as fig. 2 but for “Tramontana” (left) and “Southerlies” (right) conditions during nighttime.

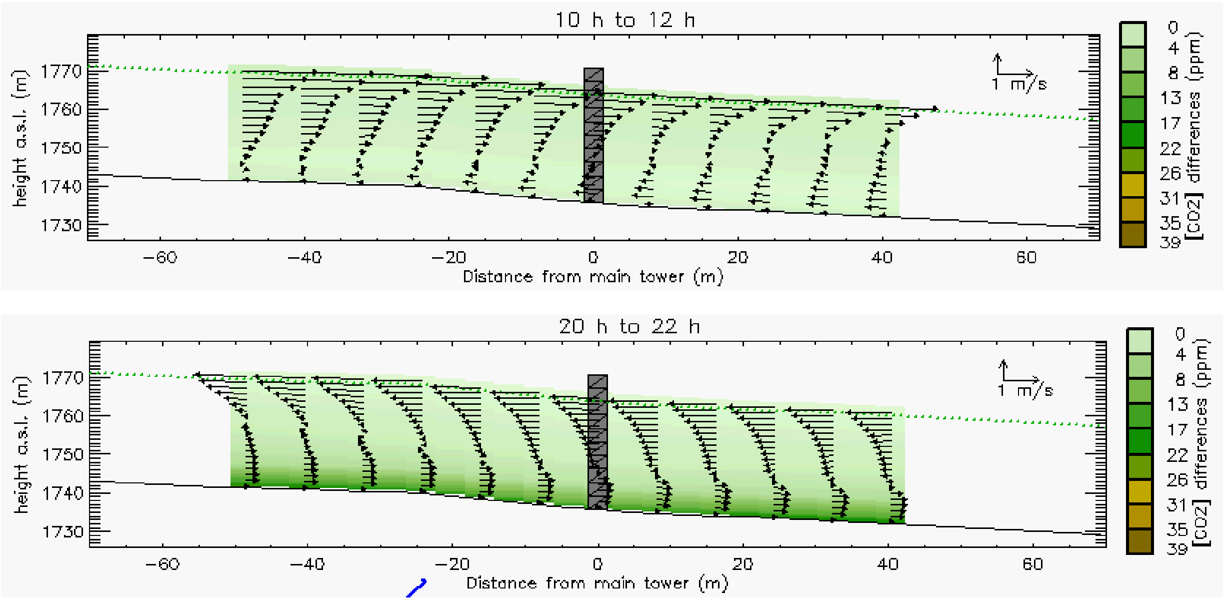

Fig. 5: Slice through the control volume along the red dashed lines in fig. 4 but for daytime (10 h-12 h) during "Tramontana" conditions (top) and for nighttime (20 h - 22 h) during "Southerlies" situation (bottom).

drainage flow during nighttime and suppresses the upslope flow above the forest canopy during daytime. Since the CO_2-gradient develops similarly like under local conditions, despite of supposed better mixing of the air in the canopy space, the significantly higher wind speeds (fig. 4 left) increase the amount of F_{HA} during these conditions. Interestingly, the buoyancy in the canopy during the day is strong enough to enforce an upslope flow in the trunk space south of the main tower as shown in fig. 5 (top).

4.2 Southerlies

Similar to the "Tramontana", periods with continuing flow but from the south were observed. During these "Southerlies" situations, the local daytime upslope flow is supported and enhanced compared to local conditions. During nighttime, the downslope flow is only established in the trunk space and most pronounced early in the night. In the crown space and above the canopy the wind blows consistently upslope all night long. This leads to periods of several hours with opposite flow directions in and above the canopy and extreme wind shear. The effect of such flow patterns on the amount of F_{HA} is exactly the contrary when compared to the "Tramontana" situation. The positive non turbulent horizontal advective flux in the trunk space is compensated by the flux invoked by the upslope winds in the crown space and above the canopy during nighttime.

5. DISCUSSION

5.1 Vertical advection

The mean diurnal courses of F_{VA} and its components are shown in fig. 6. The components mean vertical velocity and the vertical CO_2 concentration gradient (and thus F_{VA}) are strongly dependent on the respective meteorological conditions. The vertical concentration gradient is lower at night during "Tramontana" and "Southerlies" conditions because of better mixing of the air in the canopy due to higher wind velocities ("Tramontana") or extreme wind shear ("Southerlies") compared to the "local" situation. According to eq. (1) the sign of F_{VA} is determined by the direction of the tilt corrected mean vertical wind component, because the vertical CO_2 concentration gradient is always negative at night. F_{VA} is therefore generally positive at night because of mean downward flow (negative w). However, as shown in fig. 6, this pattern is modified against nearly zero mean F_{VA} during "Tramontana" conditions, but with large scatter. Highest F_{VA} (together with most negative mean vertical wind) is observed early at night when the wind blows upslope above the canopy but downslope close to the ground, a characteristic feature of the "Southerlies" situation.

The pattern of the mean vertical wind component probably suffers from an imperfect tilt correction algorithm as addressed in Vickers and Mahrt (2006). Though the planar

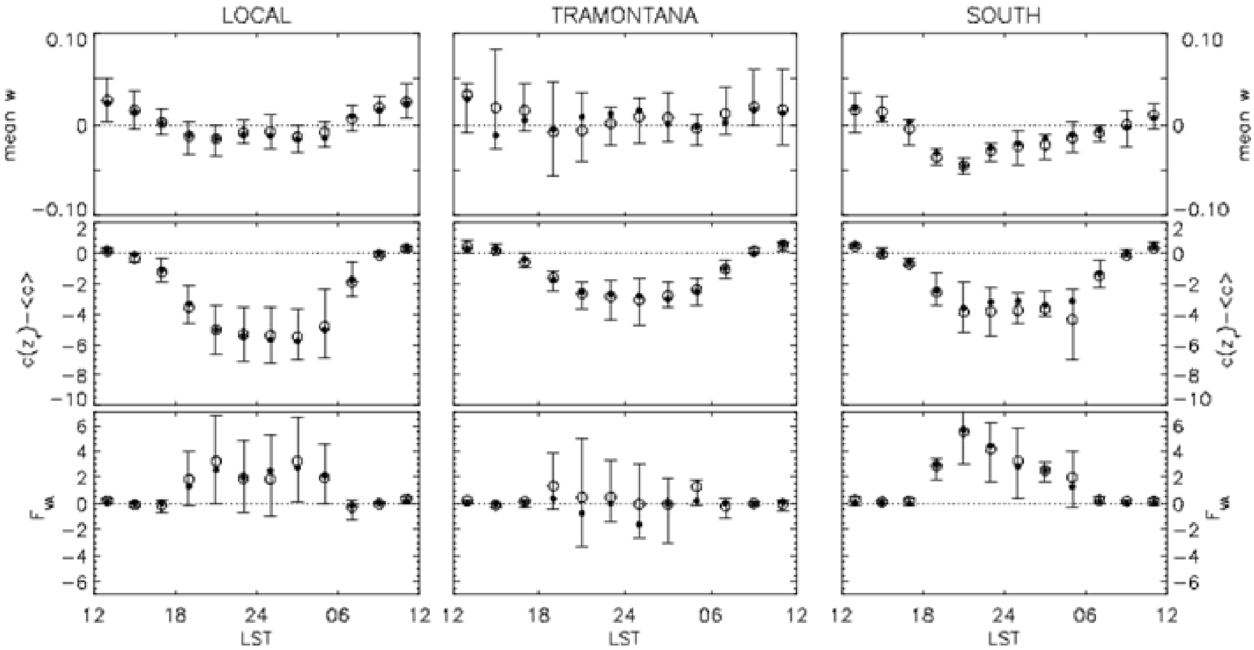

Fig. 6: Mean diurnal course of F_{VA} (bottom) and its components mean vertical wind velocity (top) and the difference between CO_2 concentrations at the reference level and in the volume below (center). Open circles refer to mean values, filled circles refer to the median and error bars indicate the 50 percentile range. From left to right: "Local", "Tramontana" and "Southerlies" conditions.

fit method established itself as a quasi standard tilt correction procedure for data processing in the FLUXNET community during the last years, there may be other procedures that are better suited especially for complex terrain as at the site under consideration. One could for example consider applying the planar fit correction separately to the three meteorological situations under consideration. This will change nothing for the local situation, but would probably reduce the amount of the vertical wind component and thus also F_{VA} substantially for "Southerlies" conditions. A detailed investigation of this subject is however out of the scope of this paper.

5.1 Horizontal advection

Fig. 7 shows the main characteristics of F_{HA} under the discussed meteorological and synoptic conditions. The region of largest F_{HA} is in the trunk space. Considering F_{HA} for *NEE* significantly increases the nightly source for "local" and especially for "Tramontana" conditions, but contributes not essentially to *NEE* during the "Southerlies" situation. However, at least for "Tramontana" conditions, F_{HA} occasionally reaches extremely high values which can not simply be explained by physical processes. This is not really surprising, since the same large scatter in F_{HA} was observed in the frame of the ADVEX campaign at other CarboEurope sites in Wetzstein, Germany and Norunda, Sweden, though under completely different topography, but with the same experimental setup (Feigenwinter et al., 2008). In fact, most advection studies report large day to day variability of the non turbulent advective fluxes. Nevertheless, if averaged over a sufficient long period, consistent patterns can be derived, which provide a qualitative but also a quantitative estimate of F_{HA} and its impact on *NEE*.

6. SUMMARY AND CONCLUSIONS

The present study investigates how the vertical and horizontal CO_2 transport is governed and modified by a persistent slope wind system under different meteorological conditions, distinguishable by the differing direction of the above canopy flow from the most frequent "local" situation. The main deviations from the local slope wind system are the downslope flow during daytime for "Tramontana" situations and, vice versa, the upslope flow during nighttime for "Southerlies" conditions. During these periods, the flow in the canopy still develops according to the classical rules of slope wind systems (upslope wind during the day and downslope wind during the night) but is modified by the synoptically induced flow above the canopy. This results in a substantial amplification and

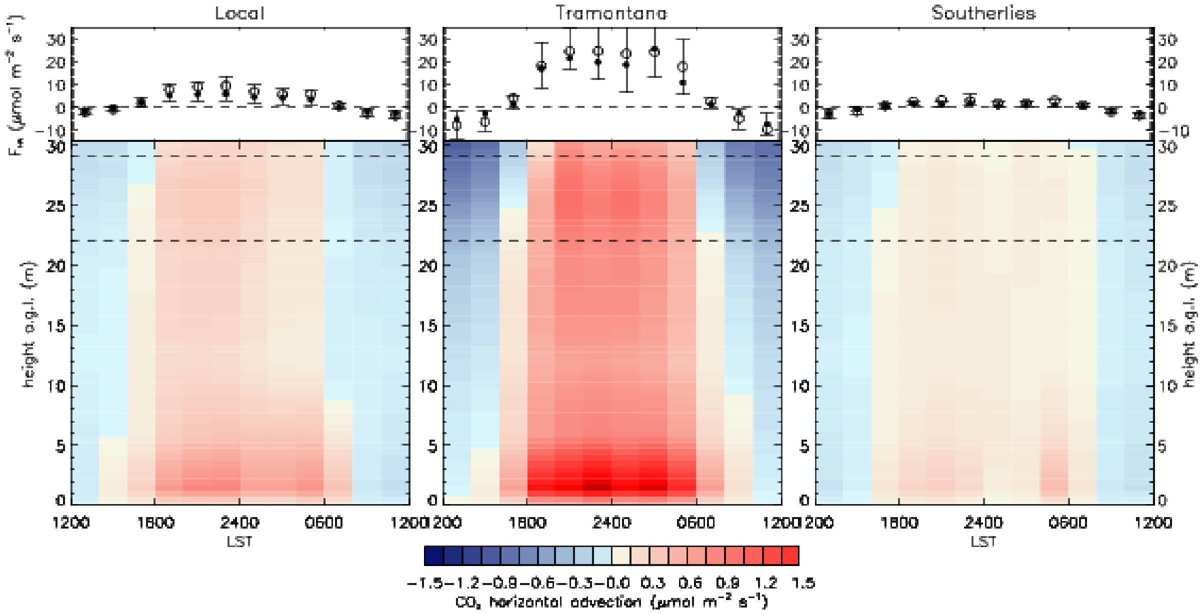

Fig. 7: Bottom: Evolution of mean F_{HA} with height. Top: diurnal course of F_{HA}. Open circles refer to mean values, filled circles refer to the median and error bars indicate the 50 percentile range. From left to right: "Local", "Tramontana" and "Southerlies" conditions.

attenuation of the "normal" flow. Depending on the magnitude and the direction of the horizontal and vertical CO_2 concentration gradient and the respective meteorological situation, the pattern of the non turbulent CO_2 transport, as expressed by vertical advection F_{VA} and horizontal advection F_{HA}, experiences characteristic modifications if compared to the most common "local" situation.

Advective fluxes of CO_2 are most important during nighttime, only a weak negative F_{HA} was observed during the day. As a consequence, the "local" positive horizontal advective fluxes F_{HA} are enhanced during "tramontana" situations and reduced during "southerlies" conditions, because the horizontal CO_2 concentration gradient is always similar (highest CO_2 concentration in the south) for nighttime periods. It's assumed that the gradient results from land-use change and source heterogeneities. About 150 m in upslope direction of the main tower is a pasture, which is assumed respiring less CO_2 than the forest. Additionally, the densest forest and the highest trees are located in downslope direction of the main tower.

In contrary to F_{HA}, the vertical advective flux F_{VA} is significantly enhanced during "southerlies" conditions. This mainly results from the relatively large negative value of the vertical wind component in the early night, when the wind shear is largest.

Since the turbulent CO_2 flux during nighttime is generally small at the Renon site, adding the advective fluxes to *NEE* as suggested in eq. (2) would significantly increase nighttime *NEE* and thus reduce the reported sink (Valentini et al., 2000) of this forest. Though there is still a lot of uncertainty in the estimation of the magnitude, the consistent patterns suggest some confidence in the order of magnitude and the direction of these fluxes and their impact on long-term *NEE*. We also showed how a slope wind system in connection with the horizontal and vertical CO_2 concentration gradient influences the evolution of the non turbulent advective fluxes, and how a slope wind system may be modified by superimposed synoptic conditions. It's expected that such process-related effects also may occur at flux tower sites with similar topography and vegetation.

ACKNOWLEDGEMENTS

This work is a contribution to the CarboEurope-Integrated Project (CE-IP) of the European Commission (GOCECT2003-505572). Special thanks go to Stefano Minerbi and to the workers from the Forest Service of the Autonomous Province of Bolzano, Italy. The ADVEX field activities would not have been possible without the substantial support from all participating institutions.

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