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# Analysis of periods with strong and coherent $CO_2$ advection over a forested hill

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**Abstract**

Horizontal and vertical advective fluxes of $CO_2$ measured during the CarboEurope-IP advection experiment (ADVEX) at the Wetzstein spruce forest site in Thuringia, Germany, were related to wind direction, stratification regime and friction velocity $u$*. Measurements of wind speed and direction carried out at one of the slopes of the ridge revealed the existence of reverse flow below the canopy on the downwind side. This uphill flow occurred concurrently with the advective fluxes measured at the top of the hill. Such result is in agreement with recent modeling works that support the existence of advection at low hills covered with a canopy. Another experimental evidence that suggest a link between advection at this site with the flow over the hill came from the analysis of the horizontal gradient of $CO_2$ inside the volume formed by the ADVEX towers. It was observed that $CO_2$ accumulated near the downwind side of the crest for cross-ridge flows, what is consistent with another modeling work of the transport of scalars across a low hill covered with a canopy.

**Keywords:** Forest ecosystems; Advection; Net ecosystem exchange; Carbon balance; ADVEX

## 1. Introduction

Long-term measurements of $CO_2$ net ecosystem exchange (NEE) between forests and the atmosphere using the eddy covariance technique are known to underestimate carbon fluxes during calm and stable nights (Goulden et al., 1996; Massman and Lee, 2002). The widespread use of the eddy covariance technique (Moncrieff et al., 1997; Aubinet et al., 2000) over several networks of measurements (e.g. EuroFlux, Ameriflux, LBA) brought to attention a variety of potential sources of problems when measuring turbulent fluxes over tall forests. The lack of energy balance closure, the influence of local circulations and low frequency motions, and the presence of subcanopy flow are examples of such complications (Mahrt, 1998; Sun et al., 1998; Wilson et al., 2002; von Randow et al., 2002).

The underestimation of nighttime fluxes of $CO_2$ is confirmed at several sites when these fluxes are compared with independent chamber measurements. The fluxes of $CO_2$ are generally lower during conditions of low wind speeds and stable stratification while chamber measurements do not confirm such low values of ecosystem respiration. During daytime the turbulent mixing is responsible for most of the exchange of scalars between the forest and the atmosphere. During nighttime, most of the $CO_2$ released from the soil and living tissue of vegetation is not measured by the eddy covariance system due to the lower turbulent activity and accumulates below the canopy. In order to overcome this problem the storage of $CO_2$ below the measuring point is calculated using a vertical profile of $CO_2$ measurements and added to the turbulent flux (Baldocchi et al., 2000; Xu et al., 1999; Aubinet et al., 2005). However, $CO_2$ is transported out of the local ecosystem if horizontal gradients of $CO_2$ are associated with horizontal motion. This effect is typically caused by drainage flow and can affect measurements made even over gentle topographies (Mahrt et al., 2001; Soler et al., 2002; Yi et al., 2005). In order to quantify the contribution of this non-turbulent flux to the NEE, Lee (1998) proposed the inclusion of an additional term, the vertical advection, which would account for the convergence/divergence of scalars as $CO_2$ over a sloping terrain. This author considered only the vertical advection, assuming that the horizontal component was negligible. In recent years the micrometeorological community recognized that horizontal advection is also an important component of the carbon balance, what led to the realization of several experiments using 2D and 3D configurations (Aubinet et al., 2003; Marcolla et al., 2005; Staebler and Fitzjarrald, 2004; Feigenwinter et al., 2004; Feigenwinter et al., 2008; Tôta et al., 2008).

In order to determine the influence of the topography on the flow one can undertake the modeling approach or perform extensive measurements at a given site. The latter approach was implemented in the CarboEurope-IP Advection Experiment (ADVEX), which took place at three sites with different topographies, measuring the advection of $CO_2$ using the same methodology (Feigenwinter et al., 2008). One of the locations was the Wetzstein site, located in Thuringia, Germany.

The annual carbon balance of the Wetzstein site for 2002 was reported by Anthoni et al. (2004) to be almost neutral and highly dependent on the friction velocity ($u_*$) threshold chosen in the gap-filling procedure. Usually, the value of $u_*$ where the curve of nocturnal respiration levels off is taken as the threshold for $u_*$ filtering. For this site, the determination of this threshold was uncertain because the curve of nighttime $CO_2$ fluxes versus $u_*$ did not level off for high turbulent mixing conditions, caused by unusually high values of ecosystem respiration frequently observed during nights with high values of $u_*$.

According to Zeri (2008), the high nighttime turbulent fluxes occurred during neutrally stratified nights associated with high values of $u_*$. These conditions were most frequently observed for winds from the southwest, the main wind direction at the site. The nighttime turbulent fluxes of $CO_2$ were considered high when they exceeded 5 µmol $m^{-2}$ $s^{-1}$. This value is in agreement with the values observed at the similar site of Waldstein/Weidenbrunnen (Rebmann et al., 2004). Additionally, extensive measurements of soil respiration during the ADVEX experiment found a uniform surface source at the area and no values of soil respiration that could justify the high ecosystem respiration of this site. Unusually high nighttime eddy fluxes were hypothesized in several works to be caused by the pressure pumping effect, when $CO_2$ is released from the soil due to changes in the pressure field below the canopy (Malhi et al., 1999; Massman and Lee, 2002; Staebler and Fitzjarrald, 2004; Ruppert et al., 2006). The pressure changes would be caused by the penetration of strong turbulent bursts in the canopy space. Shaw and Zhang (1992) observed changes in the turbulence intensity caused by changes in the pressure field below the canopy. However, such hypothesis could not be confirmed at the Wetzstein site, as it would require detailed measurements of air pressure below the canopy.

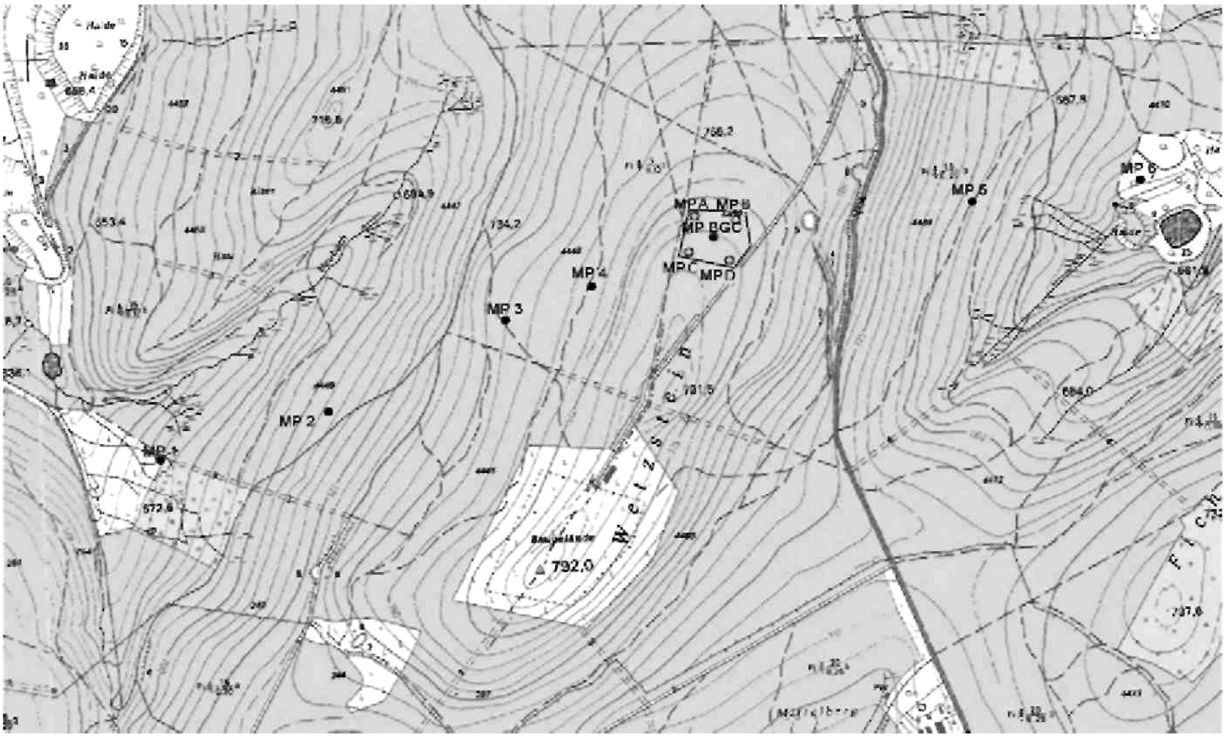
The unusual carbon balance and the difficult terrain conditions provided strong motivation to carry out the Advection Experiment (ADVEX) at the Wetzstein site. The analysis of the results from the ADVEX experiment revealed different patterns of vertical and horizontal advection depending on site characteristics such as wind direction and topography (Feigenwinter et al., 2008). For the Wetzstein site, horizontal and vertical advection of $CO_2$ were related to winds from east-southeast and from west to northwest. Vertical advection was small in comparison with the other two sites where the experiment took place (Norunda, Sweden, and Renon, Italy). Both terms were most important during nighttime periods, as expected, given that the horizontal and vertical gradients of $CO_2$ are stronger due to the lower turbulent mixing. According to Feigenwinter et al. (2008), the horizontal and vertical advection terms were on average positive and negative, respectively. A positive value of advection occurs when the average wind speed, horizontal or vertical, blows in the same direction as the respective scalar gradient. The horizontal advection term was dominant at the Wetzstein site. The low value of the vertical advection was caused by an extremely small vertical gradient of $CO_2$ when compared to other flux tower forest sites. The smaller and negative vertical advection contributed little to offset the positive horizontal advection.

The objective of this work is to explain the advective fluxes of $CO_2$ measured at the Wetzstein site. According to the first results presented by Feigenwinter et al. (2008), the advection at the site is related to special sectors of wind direction. In this work, the advective fluxes will be related to additional measurements made during the campaign, such as the stratification regime, the coupling of above- and below-canopy flows, and measurements of wind speed and direction made above and below the canopy at one of the slopes of the hill. These results will also be compared to modeling works of the flow over hills. In the next section the site and instrumentation will be described. The theory and methodology will be presented in Section 3. The results will be discussed in Section 4 and discussion and conclusions follow in Section 5.

## 2. Site and data

The Wetzstein site (50°27'N, 11°27'E) is a managed spruce forest located on a hill, at 785 m above sea level, near the village of Lehesten, Germany. The location of the main tower is indicated by the closed circle marked "MP BGC" in Fig. 1. The trees are approximately 50 years old and leaf area index was estimated to be 7 $m^2$ $m^{-2}$ by Rebmann et al. (2010). The canopy height is approximately 22 m, on average, with a very sparse understory and a well-defined trunk space up to 10 m. Precipitation is well distributed during the year with an average annual sum of 990.5 mm, and the average annual temperature is 4.9 °C (Zeri, 2008). Instrumentation and data acquisition of the main tower is described in detail by Anthoni et al. (2004).

***Fig. 1**. Topography and tower locations during the ADVEX Experiment. The main tower is marked with a closed circle (MP BGC), the slope tower is marked as MP 2 at 900 m southwest of the main tower; ADVEX towers are marked as MP A, -B, -C, and -D (open circles). ADVEX towers were located at ≈48 m from the main tower.*




The ADVEX experimental setup consisted of 4 additional towers (open circles marked as MP-A, B, C and D in Fig. 1) installed around the main tower (MP BGC). Each tower was equipped with at least four levels of high frequency (10 Hz) measurements of wind speed. Air temperature was measured at 0.5 Hz using unshielded thermocouples. In order to have the same reference temperature, all thermocouples were connected to the same data logger using a multiplexer. $CO_2$ concentration was measured at 1 Hz using gas-multiplexers connected to infrared gas analyzers (IRGAs, Li6262/ 7000, LiCor, Lincoln, US). Additionally, two perpendicular transects were set up at 1.5 m above ground in order to measure air temperature and $CO_2$. More details about the instrumentation as well as first results from the experiment can be found in Feigenwinter et al. (2008).

An additional tower (hereafter called slope tower) was installed at the southwestern slope at approximately 900 m from the hillcrest (location marked as "MP 2" in Fig. 1). This tower was equipped with 3D sonic anemometers at 2, 8.5 and 35 m. A closed-path IRGA (LICOR 6262) was installed at 35 m height so that turbulent fluxes of water vapor and $CO_2$ could be determined. The average canopy height at this location was 27 m.

## 3. Theory and methodology

The equation for the $CO_2$ budget of a forest site can be written as (Finnigan, 1999; Aubinet et al., 2003; Feigenwinter et al., 2008):

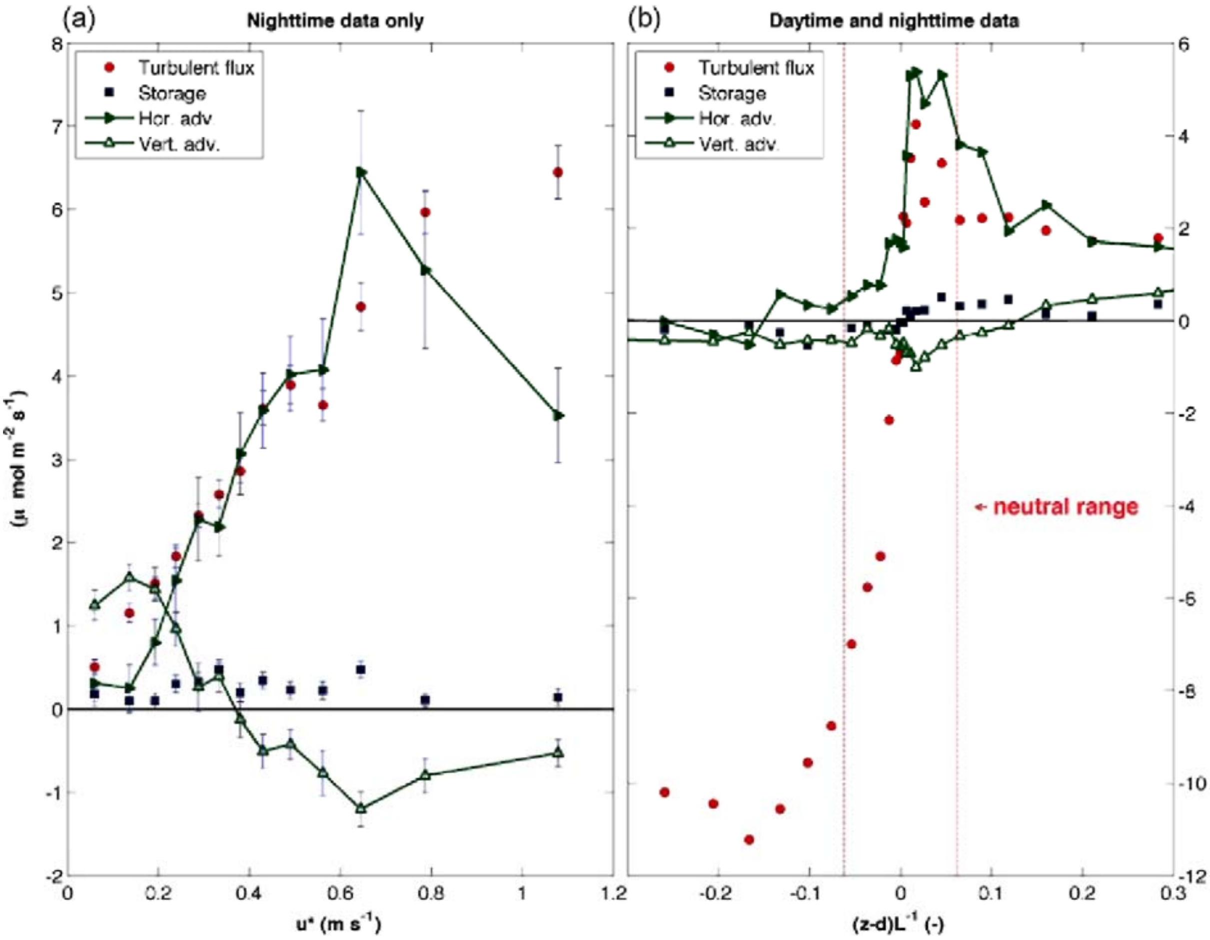
$$\mathrm{NEE} = \int_0^{z_\mathrm{r}} \frac{1}{V_\mathrm{m}} \frac{\partial \bar{c}(z)}{\partial t}\,\mathrm{d}z + \frac{1}{V_\mathrm{m}} \overline{w'c'}(z_\mathrm{r}) + \int_0^{z_\mathrm{r}} \frac{1}{V_\mathrm{m}} \bar{w}(z) \frac{\partial \bar{c}(z)}{\partial z}\,\mathrm{d}z + \int_0^{z_\mathrm{r}} \frac{1}{V_\mathrm{m}} \left( \bar{u}(z) \frac{\partial \bar{c}(z)}{\partial x} + \bar{v}(z) \frac{\partial \bar{c}(z)}{\partial y} \right) \mathrm{d}z \quad (1)$$

where $V_m$ is the average molar volume of dry air; c is the $CO_2$ mixing ratio (mole ratio of $CO_2$ to dry air); *t* is the time; *u, v,* and w are the wind components in the *x, y*, and *z* directions respectively. The overbars represent Reynolds averaging and the integrals sum from 0 to $z_r$, the measurement height. The first term on the right hand side (RHS) is the storage of $CO_2$ below the measurement height $z_r$. The second term is the vertical turbulent flux measured at the top of the tower. The third and fourth terms are the vertical and horizontal advection of $CO_2$. These terms are the result of several approximations and simplifications that included neglecting the divergence of both the horizontal and vertical turbulent fluxes, and assuming the continuity of the wind field in the horizontal domain. These approximations are discussed in detail in Aubinet et al. (2003) or Staebler and Fitzjarrald (2004).

Care should be taken regarding the approximations and uncertainties associated with the advection terms in Eq. (1). The vertical advection requires the correct calculation of the average vertical velocity. Vickers and Mahrt (2006) reported disagreements between three different tilt correction methods, including the one used in Feigenwinter et al. (2008). They concluded that the mass continuity approach was more systematic and "consistent with subsidence due to the surface roughness change" but was also more sensitive to the spatial scale used in the calculations. Nevertheless, Feigenwinter et al. (2008) reported that the uncertainty in the calculation of $\overline{w}$ "only marginally affects sites with a clear mean diurnal course of $\overline{w}$, as is the case for the Wetzstein site.

Another potential problem is the importance of the horizontal divergence of turbulent fluxes, which are generally neglected. Moderow et al. (2007) calculated the horizontal divergence of sensible heat fluxes and found that despite presenting higher values during unstable conditions, these fluxes were small in magnitude when compared to the other components of the sensible heat budget. The authors found that the divergence contributed to 5-10% of the total budget. Staebler and Fitzjarrald (2005) calculated the divergence in two forest sites in complex terrain using a subcanopy array of sonic anemometers and found that the divergence had a diurnal cycle. However, these results did not match the measurements of vertical mass flow. The authors suggested the realization of extensive measurements using a network of towers in order to reconcile the results of mean vertical velocity and divergence.

***Fig. 2**. $CO_2$ flux components plotted versus friction velocity u· (panel a) and the stratification parameter (z - d)/L, where z is the measuring height, d is the displacement height and L is the Obukhov length. Data sorted according to u> and averaged every 100 records. Error bars denote the standard error of the mean. Error bars not shown in panel b for clarity.*



An alternative method for the calculation of advection based on the mass conservation approach was proposed by Montagnani et al. (2009). They used data measured during the ADVEX experiment in the alpine site of Renon, Italy, and created 3D fields of wind velocity and $CO_2$ concentration through interpolation. They obtained advective fluxes that were in the same range found by Marcolla et al. (2005) and estimates of NEE that included advection and were better correlated to environmental drivers.

## 4. Results and discussion

According to the first results reported in Feigenwinter et al. (2008), the advective fluxes for the Wetzstein site were small in comparison with the fluxes obtained for the other two sites (Renon, Italy and Norunda, Sweden). Nevertheless, the horizontal and vertical advective fluxes had magnitudes comparable or even higher than the turbulent $CO_2$-flux and storage depending on the value of $u_*$, as can be seen in Fig. 2a. Vertical advection was the highest flux for $u_*$ lower than 0.2 $ms^{-1}$ while the horizontal advection had a comparable magnitude to the turbulent flux for well-mixed conditions ($0.3 < u_* < 0.6$ $ms^{-1}$).

The turbulent flux in Fig. 2a presented the same tendency of apparent higher respiration for high $u_*$ as reported before by Anthoni et al. (2004) and Zeri (2008). The storage term was negligible for $u_* < 0.2$ $ms^{-1}$ indicating that the $CO_2$ respired during these conditions was taken away, most probably by a combination of vertical advection and drainage flow. Indeed, the vertical advection was positive during these situations because both the average vertical velocity and the vertical gradient of $CO_2$ were negative (i.e., directed downwards). On the other hand, according to Fig. 2a and b, the strongest negative vertical advection, and the highest values of horizontal advection and turbulent fluxes occurred for high turbulent mixing and neutral stratification. These observations support the idea of $CO_2$ being brought to the top of the ridge by the effects of the flow passing over the hill, given that the abundance of $CO_2$ cannot be explained by measurements of soil respiration. This topic will be further discussed in Section 4.2, when the horizontal gradients of $CO_2$ will be presented. Finally, the advective fluxes presented a tendency of lower values (absolute value) for extremely high $u_*$ ($u_* > 0.6$ $ms^{-1}$), while the turbulent fluxes increased, most probably because the higher mixing dampens the horizontal and vertical gradients and causes the available $CO_2$ to be exchanged via turbulent processes.

According to Feigenwinter et al. (2008), the vertical and horizontal advection at the Wetzstein site were associated with cross-ridge flows. Horizontal advection was positive on average and was highest for northwesterly winds. Horizontal advection was also observed for the ESE sector, but with a lower magnitude. Two patterns were identified for the average vertical advection: (1) positive vertical advection for winds blowing from 0° to ≈70°; (2) negative advection for the sectors around ESE and W-NW, the directions associated with the cross-ridge flow. The flow patterns, horizontal advection and the patterns for vertical advection will be discussed next with the help of additional data not presented in Feigenwinter et al. (2008).

### *4.1. Coupling between the above and below-canopy flows*

The Wetzstein site has a complex coupling of the flows above and below the canopy. The cross-ridge sectors around east-southeast (ESE) and west to northwest (W-NW) (approx. 110° and 300°) present in general the best coupling (Fig. 3a), probably because the streamlines were perpendicular to the topography lines for these sectors (Fig. 1). It should be noted that decoupling could also occur for these situations, caused by drainage flow associated with the stable stratification. Wind shear was observed below the canopy when the wind direction at 30 m remained constant around 240° (southwest, Fig. 3a) while the direction below the canopy ranged from 240° to 300°. Small changes in wind direction around 240° at the top forced the flow below the canopy to turn right, down the steep slope.

The wind below the canopy at forests over flat terrain is expected to turn left (anti-clockwise direction), according to modeling and experimental works (Lee et al., 1994; Pyles et al., 2004; Su et al., 2008). The equation for the momentum along the longitudinal direction for a homogeneous forest under steady state conditions can be expressed as:

$$\frac{\partial\overline{-u'w'}}{\partial z} = \frac{1}{\rho}\frac{\partial P}{\partial x} + C_{\mathrm{d}} a \vec{u} |\vec{U}| \qquad (2)$$

where the term on the left-hand side of Eq. (2) is the vertical divergence of the longitudinal kinematic eddy flux of momentum $(\overline{-u'w'})$, the first term on the right-hand side is the mean longitudinal kinematic pressure gradient and the second term is the drag caused by plant elements on the mean flow, with $C_d$ being the drag coefficient, $a$ the element area density, $\vec{u}$ the velocity component on the longitudinal direction and $\vec{U}$ the horizontal velocity vector (Lee et al., 1994).

According to Lee et al. (1994), the negligible vertical divergence of momentum flux close to the forest floor causes the horizontal pressure-gradient force to balance the drag force. As a result, the mean wind aligns with the mean horizontal pressure-gradient force resulting in the expected anti-clockwise turn of the wind speed. On the other hand, wind direction shear in the reverse direction (clockwise) was observed at the lowest levels by Pyles et al. (2004). The reverse wind shear was attributed to nocturnal drainage of cold air and up-valley flows during the day, given that the site was located at a valley. For the Wetzstein site, the clockwise rotation of the subcanopy wind for the southwest direction could be associated with the hypothesized pressure gradient produced by the flow passing over the hill (Finnigan and Belcher, 2004; Belcher et al., 2008). However, additional measurements of the vertical divergence of momentum flux and pressure along the ridge would be required to confirm such hypothesis.

The investigation of the wind direction above and below the canopy at the slope tower (Fig. 3b) revealed that the subcanopy space was decoupled from the flow above the canopy most likely due to drainage of cold air (wind direction around 110° at 2 m). Most of the cases for this sector were associated with $u_*$ lower than 0.4 $ms^{-1}$ (values not shown). This figure also presents the reverse flow below the canopy for winds above the forest blowing from ≈100°, which will be discussed in Section 4.2. The reverse wind shear can also be observed from 210° to ~270° at the horizontal axis.

*4.2. Advection and cross-ridge flows*

From the analysis of the time series of horizontal and vertical advection two patterns were evident: (1) positive horizontal advection and negative vertical advection for cross-ridge flow from the ESE sector; (2) positive horizontal advection for cross-ridge flow from the northwest. The first pattern was observed during a continuous period of six nights in early May (DOY 123-124 to 129-130, Fig. 4) and two other nights in early June (data not shown). The results in Fig. 4 reveal that advection was triggered by the change in wind direction (from southwest to east).

The hill at the Wetzstein site is oriented approximately to north-northeast (Fig. 1). The flow coming from the cross-ridge sectors (ESE and W-NW) tend to pass over the hill depending on the wind speed and stratification regime (Stull, 1988). According to several recent modeling works, the flow passing over a low hill covered with a canopy disturbs the wind speed above and below the vegetation layer. The effect expected is the speed-up of the flow on the upwind slope and the slow-down on the downwind slope of the ridge (Finnigan and Belcher, 2004). The combination of both effects causes the air from the downwind and upwind sides of the ridge to converge at the hillcrest, creating a "chimney" of scalars that are transported across the hill (Katul et al., 2006).

Support for these modeling approaches came from additional measurements performed at the slope tower (Fig. 5). In this figure the wind directions below and above the canopy were plotted for a period before and after the onset of advective fluxes shown in Fig. 4. After DOY 123 the wind direction at 35 m changes to east, causing the difference to the wind direction below the canopy to be about 180°. While the wind at the top is blowing downhill, the wind at 2 m blows uphill. The insets show the vertical profile of wind speed, zoomed to show only the heights below the canopy, each being the average for the time between 00:00 and 00:30 h. According to these profiles, the wind speed at the lower level is always higher than the wind speed at 8.5 m, suggesting the existence of a "canopy jet" at 2 m.

The existence of reverse flow below the canopy at the downwind side of the hill is hypothesized in the modeling work of Finnigan and Belcher (2004). According to the authors the air passing over the hill has a higher speed at the hillcrest, given the distortion in the streamlines caused by the underlying topography. The higher wind speed lowers the air pressure around the hilltop, creating a pressure gradient that pulls the air uphill on both sides of the ridge through a hydrodynamic pressure force ($F_p$). It is expected that above the canopy at the upwind side this forcing adds up to the inertial force induced by the wind speed. Below the vegetation, the momentum is partially absorbed by the canopy drag and $F_p$ dominates over the gravitational push $F_g$ resulting in a net push uphill. At the downwind side $F_p$ counter-balances the inertial force of the wind speed both above and below the canopy and the net force is also uphill, causing the reverse flow.

***Fig. 3***. *Coupling of wind direction above and below the canopy for the main tower (panel a) and slope tower (panel b).*

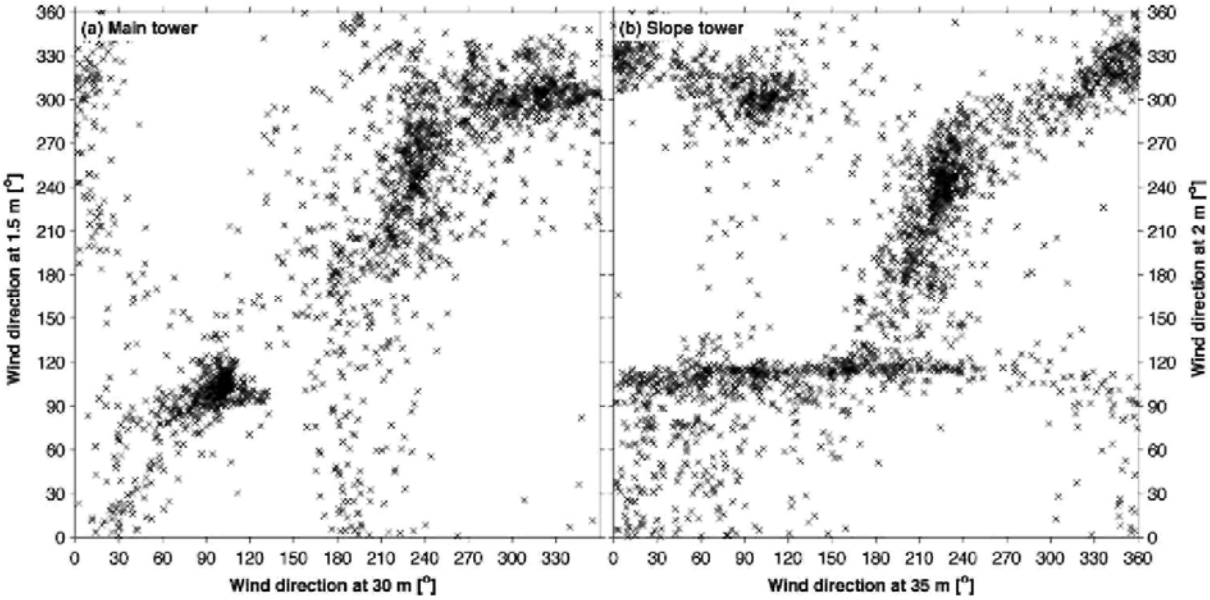



***Fig. 4***. *(a) Time series of horizontal and vertical advection, and turbulent flux, from DOY 120-130; (b) Wind direction (left scale) and net radiation (right scale); (c) friction velocity u*> at the main tower (30 m) for different stratification regimes (marked by symbols).*

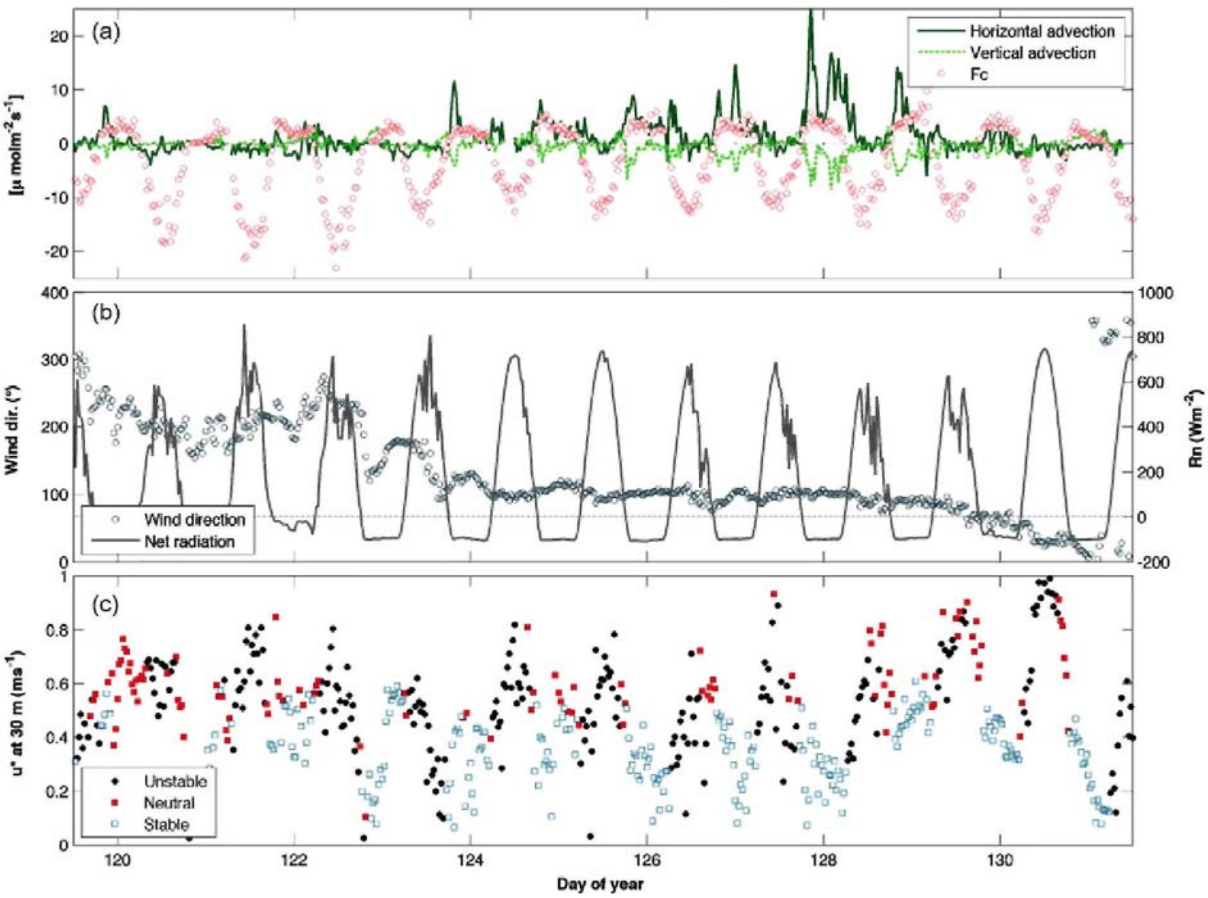
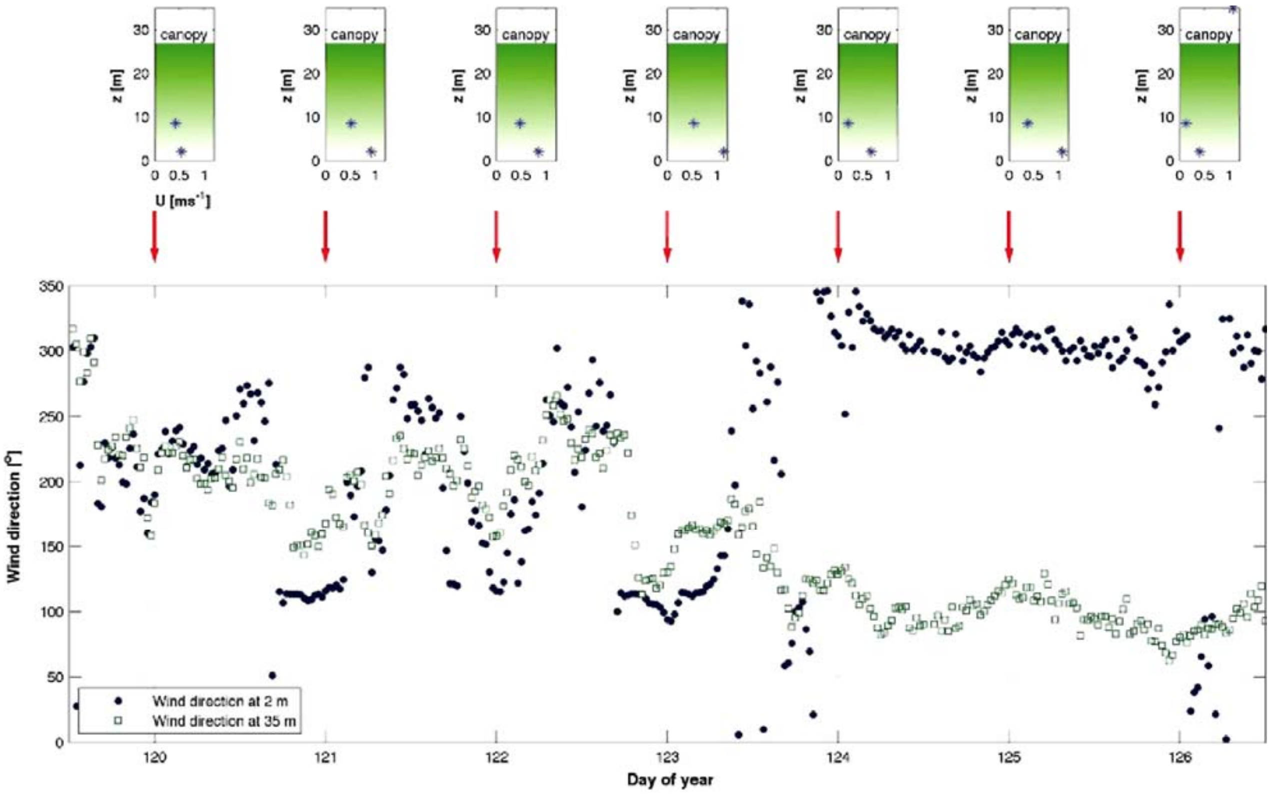


***Fig. 5***. *Wind direction above (35 m) and below the canopy (2 m) for the period before and after the onset of advective fluxes on DOY 124 (Fig. 4) at the slope tower. Half-hour averages of wind speed U ($ms^{-1}$) in 2 and 8 m height between 00:00 and 00:30 h are shown in the insets. The shaded area denotes the tree space.*




It should be noted that the period in Fig. 5 is characterized by stable and unstable stratification (nighttime and daytime, respectively) and that Finnigan and Belcher (2004) consider a neutral flow in their modeling work. Belcher et al. (2008) obtained preliminary results for the flow passing over a hill during stable conditions. They found that the hydrostatic pressure-gradient forces the cooler air below the canopy to drain down the slope. This drainage of cold air would cause a decoupling between the above-and below-canopy flows, resulting in advective transports of scalars such as $CO_2$ (shown in Section 4.3). However, in the cases of sufficient speed of the cross-ridge flow, $F_p$ (directed upslope) is large enough to overcome the hydrostatic (negative buoyancy) force. The resulting direction of the subcanopy flow is then upslope.

Indeed, the wind speed at the hillcrest during the cross-ridge event (DOY 124-126 in Fig. 5) was on average 1 $ms^{-1}$ higher compared to the previous days (3 $ms^{-1}$ before DOY 124 and 4 $ms^{-1}$ after, with peaks of 5 $ms^{-1}$). This offset remained constant during day and night until DOY 130, when the wind speed at the crest matched again the wind speed at the slope (both above the canopy). This strong dynamical forcing was most probably responsible for the upslope flow observed for day and night, regardless of atmospheric stability. This result is an experimental evidence that reverse flow can also occur for stratification regimes other than neutral or weakly stable, as assumed in the model works of Finnigan and Belcher (2004) and Belcher et al. (2008).

Another interesting result came from the analysis of the $CO_2$ differences below the canopy for the conditions of cross-ridge flows. Recent modeling works of the flow over a low hill covered with a canopy has demonstrated that a scalar quantity as $CO_2$ accumulates on the lee side of the ridge (Patton, 2007). The model makes use of the Large-Eddy Simulation approach and simulates the scalar transport over the hill. This accumulation occurs in the so-called recirculation zone, located on the downwind side of the hill (Poggi and Katul, 2007). Indeed, the results shown in Fig. 6 suggest that the accumulation might have occurred outside the area of the experiment, on the downwind side. According to the horizontal field of $CO_2$ differences, higher concentrations were found on the northwest corner of the experiment area, near tower A.

The results in Fig. 7b show that while the wind was blowing from northwest the surface layer was characterized by neutral stratification and high values of friction velocity for nighttime periods (panel c). These conditions promoted strong values of horizontal advection on the nights of DOY 149-150,150-151,151-152 and also on 154-155. The vertical advection was negligible during these conditions, probably because the high level of turbulent mixing dampens the vertical gradient of $CO_2$.

***Fig. 6**. [$CO_2$1 differences and wind field at different levels for easterly winds. ADVEX towers marked as A, B, C, and D; main tower marked with a star in the center.*

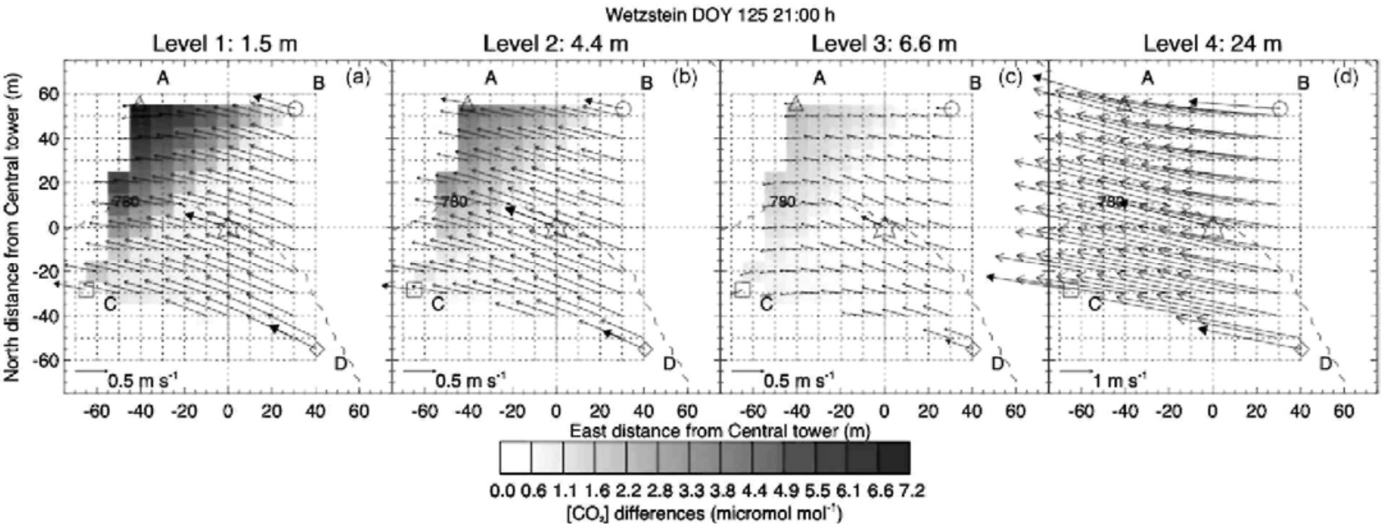
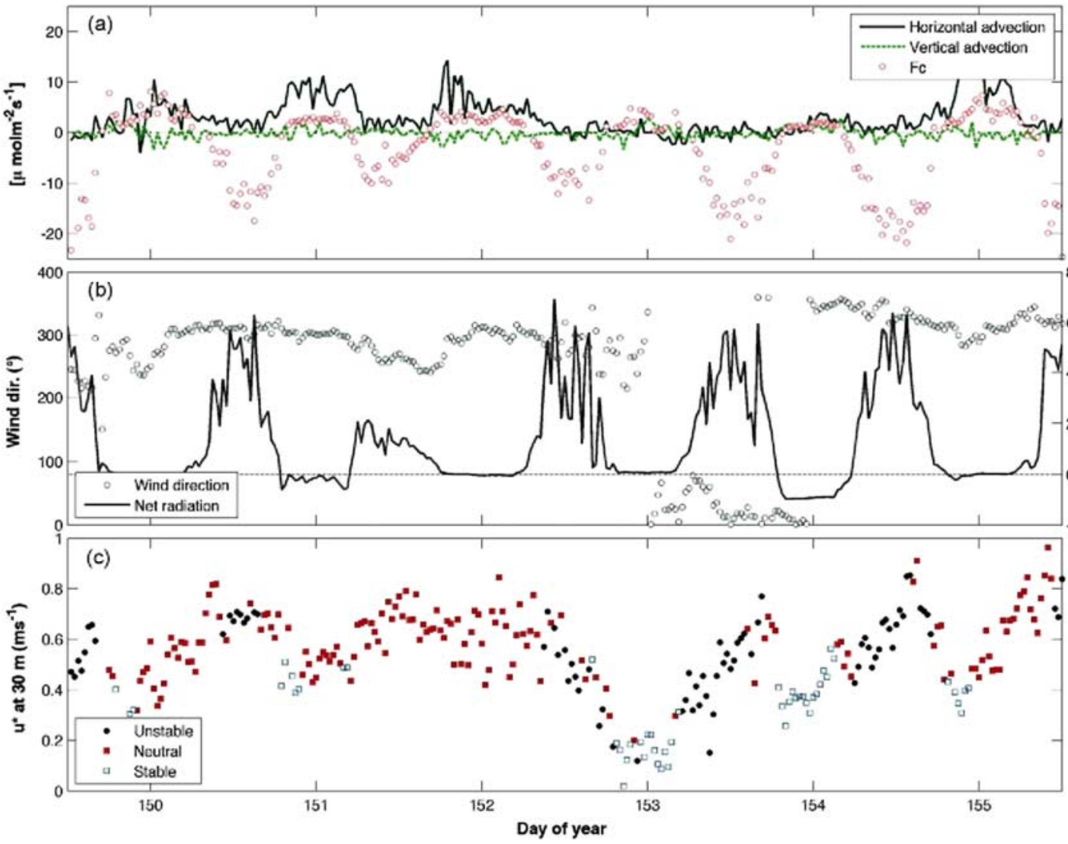



***Fig. 7.** The same as in Fig. 4, for DOY 149 (12 h) to DOY 155 (12 h).*

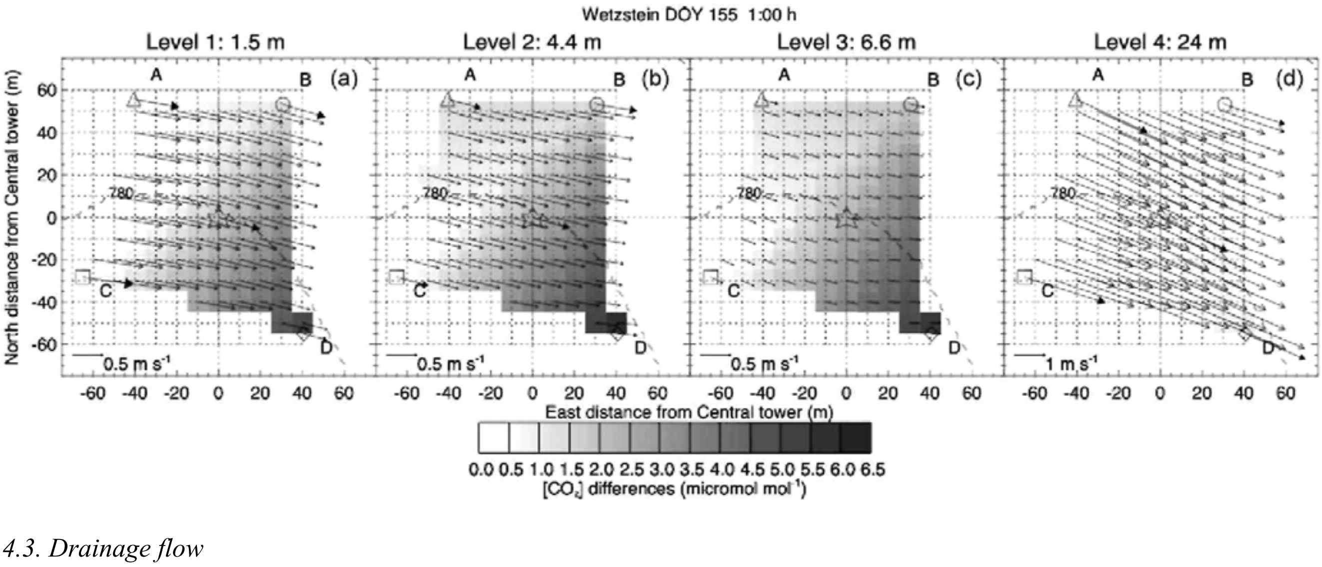


The accumulation of $CO_2$ near the downwind side of the crest was also observed for conditions of winds from the northwest sector. The same pattern shown in Fig. 6 can be seen in Fig. 8, where the situation for northwesterly winds is shown. In this figure the $CO_2$ differences indicate that highest concentrations were measured near tower D. The results in this figure and in Fig. 6 are an indication that the accumulation has occurred on the downwind side of the hill, as expected from the modeling works (Patton, 2007; Poggi and Katul, 2007). However, it should be noted that a confirmation of such meso-scale feature would require an experimental setup that would extend over a much larger area.

Due to the short duration of the experiment no other patterns of advective fluxes could be identified, besides the drainage flow described next. The easterly and northwesterly winds associated with advection were not dominant during the campaign because the main wind direction at the site is southwest. Although these periods corresponded to only 12% of the whole experiment, the advective fluxes observed are coherent with the theory of flows passing over low hills that support the existence of advection of scalars for cross-ridge flows. Horizontal and vertical advection were also observed for the southwest sector, but no clear pattern could be determined. Conditions when both horizontal and vertical advection were strong were measured as well as conditions when both terms were negligible for this sector. It should be noted that the apparent high turbulent flux observed for southwest winds and high $u^*$ might also be related to the meso-scale features that are associated with cross-ridge flows and advection. $CO_2$ brought to the hillcrest by uphill motions would be exchanged as eddy fluxes, while the high turbulent mixing would reduce the horizontal and vertical gradients of $CO_2$, decreasing advection.

Advective fluxes as determined during the ADVEX campaign were added to turbulent and storage fluxes but revealed to be not representative of the biological fluxes, as would be expected at the site. As discussed in Feigenwinter et al. (2008), the large scatter of the advective fluxes makes it difficult to use them with the NEE obtained from the eddy covariance and storage. The uncertainties in the advective fluxes might have been caused by different time scales associated with advective fluxes, what would require different averaging procedures, or methodological uncertainties related to the estimation of the average vertical velocity, important in the calculation of vertical advection. Another potential problem is that the horizontal and vertical components have different footprints compared to the storage and turbulent flux. Finally, from the analysis of Katul et al. (2006) one should expect a large variability in the velocity and $CO_2$ fields over the hill, resulting in contrasting values for advective fluxes depending on the location of the control volume

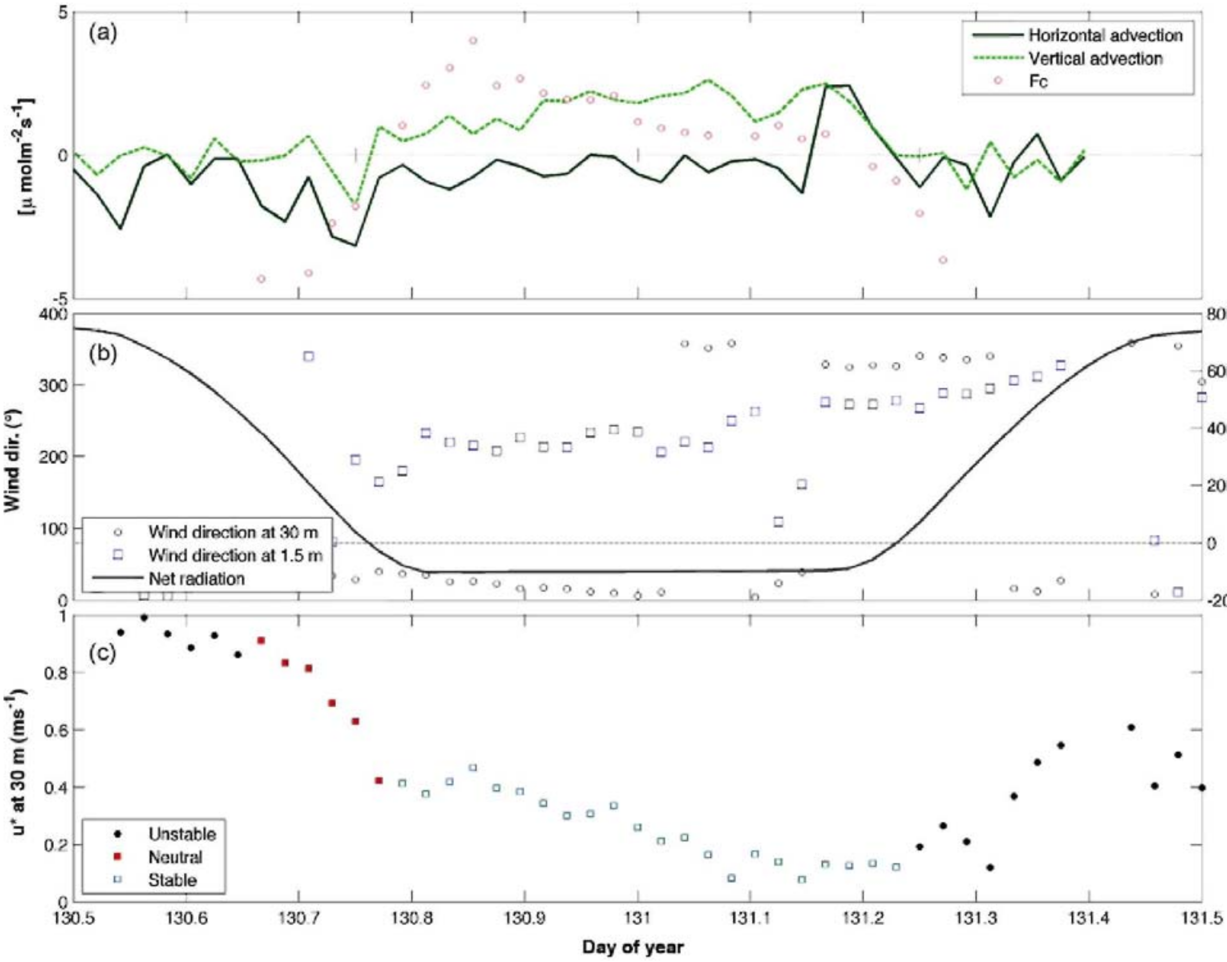
***Fig. 8**. The same as Fig. 6, for northwesterly winds.*




*4.3. Drainage flow*

The last pattern identified for the vertical advection was caused by drainage flow. This pattern can be seen in Fig. 8 of Feigenwinter et al. (2008) as the mean positive values of vertical advection for the sectors between 0° and ≈80° (north to northeast). An example of such pattern is shown in Fig. 9 for the night of DOY 130-131. According to the symbols in Fig. 9c, the surface layer was stably stratified and $u_*$ decreased from 0.4 $ms^{-1}$ in the beginning of the night to 0.2 $ms^{-1}$ later on. As a result, the below- and above-canopy spaces were strongly decoupled during these periods. While the wind direction at 30 m ranged from 0° to ≈60°, the flow below the canopy (at 1.5 m) followed the local slopes (cf. Fig. 1), resulting in wind directions from 200° to ≈250°.

***Fig. 9.*** *The same as in Fig. 4, for DOY 130 (12 h) to DOY 131 (12 h).*




## 5. Conclusions

Advection of $CO_2$ at the Wetzstein site is associated with cross-ridge flows. A reverse flow was observed at the slope on the downwind side of the hill, triggered by the same weather pattern that resulted in the onset of horizontal and vertical advective fluxes for several days. The reverse flow was observed continuously regardless of the stratification regime, caused by strong winds passing over the hill. Additionally, it was observed that $CO_2$ accumulated near the downwind side of the ridge, outside the area of the experiment. This accumulation is in agreement with results from another modeling work that included the transport of scalars in the simulation of flow over hills. It should be noted that the results from this experiment confirmed only part of the results from these modeling approaches. A complete validation of the models would require more extensive measurements and were not the scope of this experiment. Additional studies using tracers such as SF6 would be required in order to confirm the hypothesis about transport of $CO_2$ across the hill. Nevertheless, the interpretation of the patterns observed for the advective fluxes was consistent with several other measurements performed during the campaign and will certainly support the theoretical basis of advection over complex topographies. In conclusion, the advection observed during conditions of cross-ridge winds was most probably associated with the dynamics of the flow passing over the hill instead of being representative of the transport of $CO_2$ respired in the local ecosystem. Therefore, the analysis presented in this work for these patterns of advection should be regarded as a qualitative description of the potential problems that can be associated with measurements of energy and scalars in complex topography.

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