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How well do tall-tower measurements characterize the CO_2 mole fraction distribution in the planetary boundary layer?

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Abstract. Planetary boundary layer (PBL) CO_2 mole fraction data are needed by transport models and carbon budget models as both input and reference for validation. The height of in situ CO_2 mole fraction measurements is usually different from that of the model levels where the data are needed; data from short towers, in particular, are difficult to utilize in atmospheric models that do not simulate the surface layer well. Tall-tower CO_2 mole fraction measurements observed at heights ranging from 10 to 115 m above ground level at a rural site in Hungary and regular airborne vertical mole fraction profile measurements (136 vertical profiles) above the tower allowed us to estimate how well a tower of a given height could estimate the CO_2 mole fraction above the tower in the PBL. The statistical evaluation of the height-dependent bias between the real PBL CO_2 mole fraction profile (measured by the aircraft) and the measurement at a given elevation above the ground was performed separately for the summer and winter half years to take into account the different dynamics of the lower troposphere and the different surface CO_2 flux in the different seasons. The paper presents (1) how accurately the vertical distribution of CO_2 in the PBL can be estimated from the measurements on the top of a tower of height H; (2) how tall of a tower would be needed for the satisfaction of different requirements on the accuracy of the estimation of the CO_2 vertical distribution; (3) how accurate of a CO_2 vertical distribution estimation can be expected from the existing towers; and (4) how much improvement can be achieved in the accuracy of the estimation of CO_2 vertical distribution by applying the virtual tall-tower concept.

1 Introduction

Anthropogenic activity can influence the global climate in the long term through the emission of greenhouse gases, most notably carbon dioxide (CO_2) (Skeie et al., 2011; IPCC, 2013). However, CO_2 also has climate-sensitive natural sources and sinks (Friedlingstein et al., 2006; Le Quéré et al., 2009, 2010, 2013; Friedlingstein and Prentice, 2010; Piao et al., 2013). The feedbacks and interactions controlling the atmospheric amount of carbon dioxide, and hence the greenhouse effect of the atmosphere, make prediction of the CO_2 content of the atmosphere and the evolution of the global climate extremely difficult (Friedlingstein and Prentice, 2010). Mathematical models (inverse models of atmospheric transport of varying complexity) have been developed to describe the atmospheric carbon budget (e.g., Tans et al., 1989; Gurney et al., 2003; Baker et al., 2006; Butler et al., 2010; Ciais et al., 2010; Trusilova et al., 2010; Saeki et al., 2013; Broquet et al., 2013; Jiang et al., 2013; Peylin et al., 2013; and references therein) estimating surface sources and sinks of carbon dioxide. These models are used to infer CO_2 sources and sinks by comparing modeled and observed atmospheric distributions of CO_2. The information gained helps the understanding of the processes, as well as the development and control of mitigation/abatement strategies. Three-dimensional models need the spatial distribution of carbon dioxide mole fraction as input to, and as validation of, the transport models. Calibration of satellite-borne or ground-based remote sensing may also need detailed information on the vertical distribution of CO_2, especially for the lower troposphere where the density and variability are high (Font et al., 2008; Wunch et al., 2010; Pickett-Heaps et al., 2011; Tanaka et al., 2012; Miyamoto et al., 2013). Because of persistent vertical gradients in CO_2 in the planetary boundary layer (PBL) (e.g., Bakwin et al., 1998) and imperfect model parameterization of vertical mixing of the PBL (e.g., Kretschmer et al., 2012; Díaz Isaac et al., 2014), it is important to understand how a given point measurement in the PBL relates to the entire PBL vertical profile.

Until the late 1990s surface-based measurements (typically at 2–20 m above ground) were available almost exclusively for the estimation of the characteristic CO_2 mole fraction in the PBL. However, the mole fraction close to the surface may significantly deviate from that at the higher parts of the PBL even during daytime conditions due to the occasional strong vertical concentration gradient generated by CO_2 uptake by the vegetation, anthropogenic emission, as well as entrainment of free-tropospheric air or advection. Introduction of tall towers (Tans, 1991; Vermeulen, 2007) extending above the directly influenced surface layer offered better estimations, at least in principle. However, the uncertainty with which a tower of a given height estimates the CO_2 mole fraction at other elevations crucial for the 3-D transport models (see, e.g., Stephens et al., 2007; Xueref-Remy et al., 2011) has not yet been studied systematically. Without this understanding it is hard to assess the uncertainty of carbon budgets calculated by inverse models (Masarie et al., 2011).

In this study, combining tall-tower and aircraft measurements, we estimate the uncertainty with which measurements on a tower characterize the CO_2 mole fraction at different elevations above the tower within the PBL. In turn, the height of the tower required for a given uncertainty criterion can be determined. We present the trade-off between the height of the tower and the accuracy of the CO_2 mole fraction estimation at higher elevation above the tower. In principle, auxiliary measurements may be used to improve the estimation. In this study the virtual tall-tower (VTT) concept is tested. For the study the aircraft vertical profiles and tall-tower measurements performed at and over a rural Hungarian monitoring site during 2006–2008 are used. The study answers the following questions: (1) how tall of a tower would be required to provide a given accuracy up to a given elevation, and what accuracy can be achieved with a realistic tower? (2) How accurately can an existing tower estimate the CO_2 mole fraction for the higher layers of the PBL? (3) Is it reasonable to suggest co-located eddy covariance (EC) measurements to improve the representation of CO_2 distribution in the PBL by tall towers?

2 Methodology

2.1 Input data

Carbon dioxide mole fraction data used in the present study derive from western Hungary, where the Hungarian Meteorological Service and the Department of Meteorology, Eötvös Loránd University, Budapest, operate a tall-tower greenhouse gas (GHG) monitoring site (Hegyhátsál, 46°57′ N, 16°39′ E, 248 m a.s.l.) above which frequent airborne in situ CO_2 measurements were performed during 2006–2008.

The Hegyhátsál tall-tower GHG monitoring site is located in a fairly flat region, in a rural environment, with low levels of anthropogenic CO_2 emission. The immediate terrain does not modify the large-scale atmospheric conditions. At the Hegyhátsál tall-tower site the carbon dioxide dry mole fraction has been continuously monitored at four elevations (10, 48, 82 and 115 m above the ground) since September 1994, using a non-dispersive infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska, USA; 1994–2007: Li-Cor Model LI-6251; from 2007: Li-Cor Model LI-7000; Haszpra et al., 2001, 2010). The analyzer is calibrated against four CO_2-in-natural-air standards produced and certified by the Central Calibration Laboratory of the World Meteorological Organization (WMO CCL – http://www.esrl.noaa.gov/gmd/ccl/). Measurement data are publicly available at the World Data Centre for Greenhouse Gases of the WMO (WMO WDCGG – http://ds.data.jma.go.jp/gmd/wdcgg/).

The tower also hosts an eddy covariance system at 82 m above the ground for the continuous monitoring of the vertical flux of CO_2 and sensible heat. The system consists of a GILL R3-50 (Gill Instruments Ltd., Lymington, UK) ultrasonic anemometer and a Li-Cor model LI-6262 fast-response infrared CO_2/H_2O analyzer (Li-Cor Inc., Lincoln, Nebraska, USA). The system runs at 4 Hz sampling frequency. Net ecosystem exchange of carbon dioxide (NEE) is calculated using 1 h averaging time. Atmospheric CO_2 fluxes are storage-corrected using data from the co-located concentration profile measurements (Haszpra et al., 2005). For further details on the measurements see Haszpra et al. (2005), Barcza et al. (2009) and Tóth et al. (2010). The data are available at the FLUXNET database (http://fluxnet.ornl.gov/).

Airborne in situ carbon dioxide mole fraction measurements were performed over the Hegyhátsál tall-tower GHG monitoring site on board a small aircraft (Cessna 210) between 10 February and 12 November 2006, and between 8 November 2007 and 18 January 2009 as part of a European Commission-sponsored research project (CarboEurope-IP – http://www.carboeurope.org). For the measurements an AOS Airborne CO_2 Analyzer System (Atmospheric Observing Systems, Inc., Boulder, Colorado, USA) was used. This temperature- and pressure-controlled non-dispersive infrared gas analyzer could provide 1 s temporal resolution at a nominal accuracy comparable with that of the standards used for the calibration (0.1 µmol mol^{-1} – WMO, 2009). The sample air was dried by anhydrous magnesium perchlorate. The instrument compartment accommodated two small tanks regularly refilled with WMO-CCL-certified standard gases for the calibration of the instrument. During a flight the instrument was calibrated every 25 min, which was complemented by a baseline check every 150 s to compensate for any scale drift under the quickly changing environmental conditions (pressure, temperature, etc.). For the baseline check the standard of lower mole fraction was used. CO_2 mole fraction profiles were typically measured in late morning–early afternoon, from 200–250 m up to about 3000 m above the ground (a.g.l.) flying along an ascending and a descending spiral course above the underlying tall-tower monitoring site. The airborne measurement data are available at the CarboEurope-IP database (http://ce-atmosphere.lsce.ipsl.fr/DATA_RELEASE/) and from the corresponding author.

The comparability of the tall-tower-based and the airborne measurements is guaranteed by the calibration standards traceable to the same primary ones at WMO CCL, the uncertainty of which is $< 0.1\,\mu\mathrm{mol\,mol}^{-1}$ (Zhao and Tans, 2006). The continuous concentration measurements on the tower are also regularly controlled by independent flask sample measurements (Haszpra et al., 2010), and as a kind of subjective quality check the airborne measurements at the lowest elevation (typically 200–250 m a.g.l.) were compared with the simultaneous measurements at the top of the tower (115 m a.g.l.). More details on the airborne and tower measurements can be found in Haszpra et al. (2012). The CO_2 analyzer used for the vertical CO_2 flux measurements on the tower was also regularly calibrated against the directly calibrated analyzer used for the vertical profile measurements at the tower (Haszpra et al., 2001).

The airborne measurements did not provide the meteorological data needed for the direct determination of the height of the PBL. Therefore, data on the height of the planetary boundary layer were retrieved from the Meteorological Archive and Retrieval System (MARS) database of the European Centre for Medium-Range Weather Forecasts (ECMWF). PBL height data were calculated by the deterministic model in forecast time steps with 3 h temporal resolution (Beljaars et al., 2001). For the actual time of the flight (late morning–early afternoon) the PBL height was linearly interpolated between the model time steps, but occurrent decrease in the PBL height was not taken into account.

As the present study focuses on the PBL, airborne profiles could only be used when the PBL was at least 300 m high. This leaves a total of 136 CO_2 vertical profiles available for this study.

2.2 Uncertainty of the estimated vertical distribution of CO_2 mole fraction

The airborne and tall-tower in situ measurements record the vertical distribution of carbon dioxide in the lower troposphere. The mole fraction values measured aloft, representing the levels simulated by an atmospheric transport model (called "estimation height" in this paper), can be compared with the values measured below, simulating the top of a hypothetical tower (called "tower height" in this paper). In other words, the deviation of the constant vertical profile determined by the measurement at the top of the tower from the real one is determined at each estimation height. For a given tower height–estimation height pair this mole fraction deviation can be calculated for each measured mole fraction profile. These deviations form the empirical frequency distribution of the bias between the true mole fraction and the estimated one for each tower height–estimation height combination. The value of this bivariate function at any given tower height–estimation height point is a frequency distribution function; therefore, the graphical presentation of this bivariate function is hardly possible. Instead, mean, median, standard deviation and other statistical characteristics of the bias between the measured and assumed (constant) mole fraction profiles can be presented as the function of the tower height and the estimation height.

The comparison of the measured and estimated profiles gives information on how well a tower of height H could estimate the CO_2 mole fraction in the PBL higher up.

For the study the airborne in situ measurements were layer-averaged with 25 m vertical resolution from 225 m a.g.l. up to the top of the measurements, usually about 3000 m a.g.l. Any data gap in the layer-averaged profile caused, for example, by calibration or baseline check of the instrument was filled by linear interpolation between the neighboring layers as long as the gap was not wider than 50 m (two layers).

For the specific study on the mid-PBL CO_2 mole fraction the mid-PBL CO_2 mole fraction was identified as the layer average of the layer covering the mid-PBL elevation.

In this study the height-dependent performance of the hypothetical tall tower is primarily expressed on a relative scale: the estimation height is expressed as percent of the PBL height. The reason for this is the fact that a given absolute elevation can represent rather different relative ones within the PBL depending on the actual PBL depth, and gradients are functions of depth within the PBL, not absolute elevation above ground. It should also be noted that the gradient function may be different in shallow and deep PBLs, but the limited number of the available measurements does not make possible the resolution according to PBL height. The use of relative elevation scale may cause inconvenience for certain applications because the results may need to be transformed using the actual PBL height.

2.3 The virtual tall-tower concept

The virtual tall-tower concept was first presented by Davis (2005). Using the mixed-layer similarity theory of Wyngaard and Brost (1984) and Moeng and Wyngaard (1984), theoretical (idealized) scalar profiles can be estimated for the entire PBL, taking into account surface fluxes, convection and entrainment processes. In our case, CO_2 mole fraction profiles can be estimated for the entire PBL based on the vertical flux measurements performed on the tower and the available tower-based or airborne CO_2 mole fraction observations. Practically, the CO_2 concentration gradient is estimated between the observation level and the estimation height defined in the previous section.

Following the work of Wyngaard and Brost (1984) and Moeng and Wyngaard (1984), the CO_2 mole fraction gradient in the PBL can be given in the following form:

$$\frac{\partial C}{\partial z} = -g_\mathrm{b}\left(\frac{z}{z_i}\right)\frac{\overline{cw_\mathrm{s}}}{z_i w_*} - g_\mathrm{t}\left(\frac{z}{z_i}\right)\frac{\overline{cw_1}}{z_i w_*}, \tag{1}$$

where C is the CO_2 dry mole fraction; $\overline{cw_\mathrm{s}}$ is the CO_2 vertical flux at the surface; $\overline{cw_1}$ is the CO_2 flux at the top of the mixed layer (due to entrainment); z_i is the boundary layer height; z is the height above the ground; $g_\mathrm{b}(z/z_i)$ and $g_\mathrm{t}(z/z_i)$ are dimensionless bottom-up and top-down gradient functions, respectively (functions of dimensionless height z/z_i); and w_* is the convective velocity scale defined as

$$w_* = \left(\frac{g\overline{\theta w_\mathrm{s}} z_i}{T}\right)^{\frac{1}{3}}. \tag{2}$$

In Eq. (2) g is the acceleration due to gravity, $\overline{\theta w_\mathrm{s}}$ is the potential temperature (buoyancy) flux at the surface and T is the surface layer virtual potential temperature. Potential temperature flux can be derived from the sensible heat flux measured at most sites where the EC technique is applied.

In Eq. (1) the first term represents the bottom-up diffusion, while the second term is the top-down diffusion caused by entrainment.

Theoretically, $\overline{cw_1}$ might be estimated from the following equation (Eq. 9 in Wyngaard and Brost, 1984):

$$\overline{cw_1} \approx \frac{-\partial h_1}{\partial t}(C_2 - C_1). \tag{3}$$

Here C_2 is the CO_2 mole fraction above the boundary layer (free-tropospheric background), and C_1 is that at the top of the boundary layer. In the present study the airborne in situ measurements are used to estimate C_2. In a few cases (14 days) the PBL was higher than the highest available measurement level. For those days, as there was no other choice, the marine boundary layer reference mole fraction (GLOBALVIEW-CO2, 2012) was used as the free-tropospheric background. The top of the tower value is used to represent the boundary layer top mole fraction (C_1).

At a monitoring site, where eddy-covariance-based CO_2 and sensible heat flux measurements are available, this concept can be used for the estimation of the CO_2 mole fraction gradient if the flux measurements can be considered as representative of the surrounding region.

The proposed forms of $g_\mathrm{b}(z/z_i)$ and $g_\mathrm{t}(z/z_i)$ of Wyngaard and Brost (1984) were further modified by Moeng and Wyngaard (1984), who proposed an alternative $g_\mathrm{t}(z/z_i)$ due to better fit to the original data presented by Wyngaard and Brost (1984). Apart from the functions published by Moeng and Wyngaard (1984), there are alternative functional forms for the bottom-up and top-down gradient function. Patton et al. (2003) proposed an alternative $g_\mathrm{b}(z/z_i)$ but suggested using the original $g_\mathrm{t}(z/z_i)$ proposed by Moeng and Wyngaard (1984). Wang et al. (2007) suggested a replacement for both $g_\mathrm{b}(z/z_i)$ and $g_\mathrm{t}(z/z_i)$ (note that both Patton et al. (2003) and Wang et al. (2007) calculated the functions for sites with forest canopies). Uncertainty in the application of the VTT method might arise due to the improper selection of the gradient functions $g_\mathrm{b}(z/z_i)$ and $g_\mathrm{t}(z/z_i)$.

In order to find the most appropriate functional form for the application of the VTT concept, we tested all three gradient functions mentioned above and identified those that best matched the data (see the Supplement). The integrated form of the gradient function that proved to be the most appropriate is the following:

$$C = 5.3\frac{\overline{cw_\mathrm{s}}}{w_*}\left(\frac{z}{z_i}\right)^{-\frac{1}{5}} - 0.7\frac{\overline{cw_1}}{w_*}\left(1 - \frac{z}{z_i}\right)^{-1} + \text{constant}. \tag{4}$$

The gradient function may depend on local environmental conditions (e.g., on-site heterogeneity); therefore further studies on this topic are desirable. We used Eq. (4) for the estimation of the mole fraction difference between the top of the tower (where the actual measurement is carried out) and the estimation height. Based on the VTT concept, CO_2 mole fraction gradients were estimated for the PBL using 75 airborne vertical profile measurements. For the other profiles the VTT concept was not applicable mainly due to non-positive sensible heat flux or incomplete data. The CO_2 mole fraction differences were estimated in discrete 25 m elevation steps. CO_2 mole fraction differences between the assumed measurement elevation and the estimation height were calculated using Eq. (4), and then the calculated mole fraction was compared with the actual one measured by the aircraft (225–3000 m) and the tower at Hegyhátsál (10–115 m). This procedure resulted in a frequency distribution of differences at each tower height–estimation height combination, similar to that in the case of the hypothetical physical tower. The comparison of the median biases resulting from the simple extrapolation (constant profile assumption) and that supported by the VTT concept shows how much the application of the VTT concept (supposing the operation of an EC system on the tower) would improve the estimation of the CO_2 mole fraction at levels in the PBL above the tower. Due to the mathematical form of Eq. (4), CO_2 mole fraction gradients often became unrealistically high close to the top of the PBL (as z/z_i approaches 1); thus the VTT concept is only studied up to the 95 % of the PBL height.

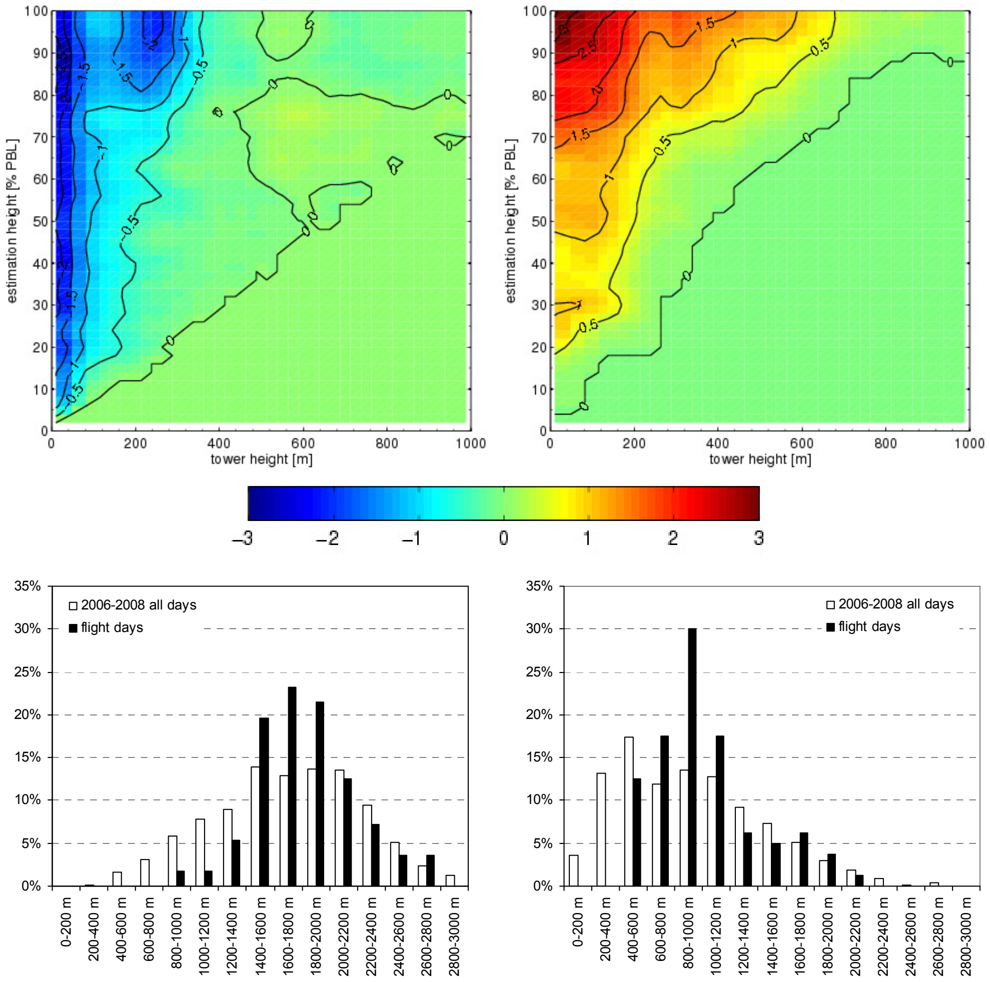

Figure 1. The median bias between the true CO_2 mole fraction and the estimated one as a function of the height of the hypothetical tower (tower height) simulated by the aircraft or the existing tower and the relative height within the PBL for which the mole fraction is extrapolated (estimation height) from the measurements at the top of the hypothetical tower (μmol mol^{-1}). A negative sign means underestimation by the measurements. Left: summer; right: winter. Bottom panels show the 12:00 UTC PBL-height statistics for all days during the period of 2006–2008 and for the days of the flights.

Convective velocity scale and surface fluxes were calculated using the results of the eddy covariance measurement the closest in time to the middle time of the airborne measurements. In order to provide more robust estimation of simulated gradients, convective velocity scale and surface flux data available in 1 h resolution were averaged for 3 h starting 3 h before the middle time of the airborne measurements. The averaging is also useful as it decrease the random flux error inherently present in the eddy covariance measurements.

3 Results

3.1 Quantification of the bias between the tower height and the estimation height

The simplest approach to using tower CO_2 data to estimate the PBL mole fraction is to assume that there is no vertical gradient, as described in Sect. 2.2. Figure 1 shows the median bias between the observed (by aircraft) CO_2 mole fraction and the estimated one following this well-mixed PBL assumption as the function of both the estimation height (y axis) and the tower height (x axis). The tower height CO_2 mole fraction was observed on the tower at Hegyhátsál or using the aircraft at higher elevations. As a tower may have several air inlets from the ground up to its top, it is assumed that the CO_2 mole fraction below the top of the tower is exactly known; that is, the bias is 0. Given the different CO_2 sur-

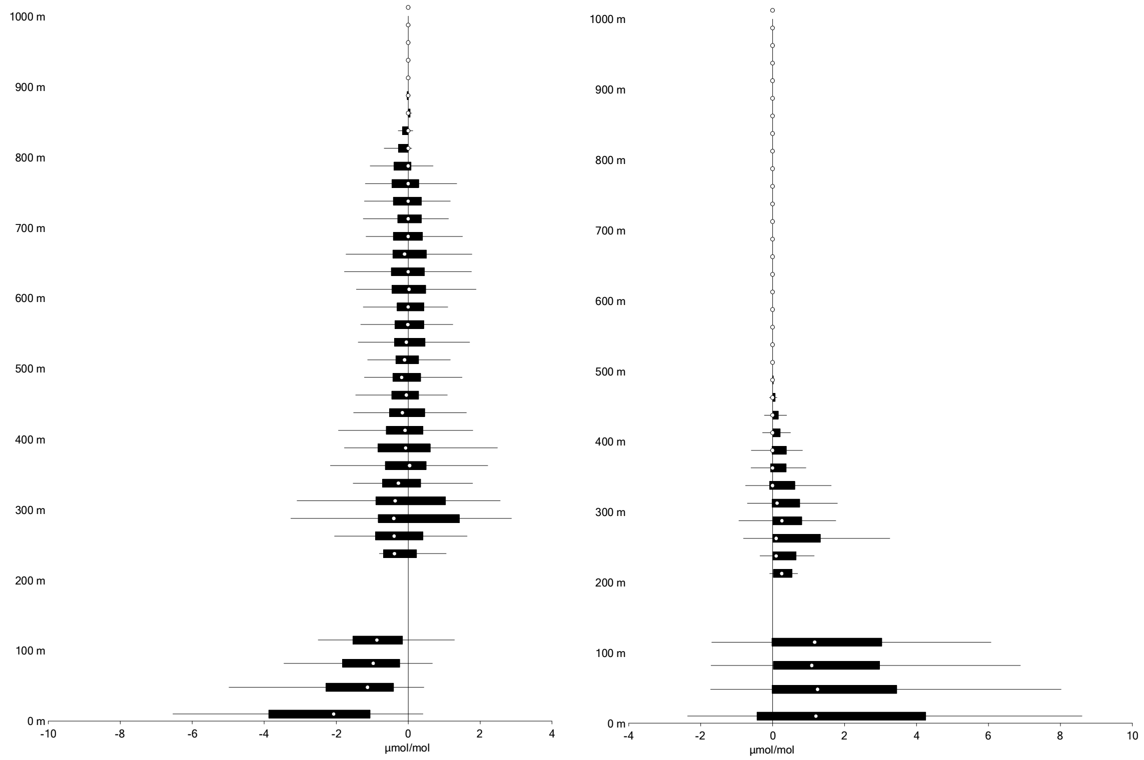

Figure 2. Empirical frequency distribution of the differences between the CO_2 mole fraction measured at the top of a tower of a given height (tower height) simulated by the aircraft or the existing tower and the mid-PBL CO_2 mole fraction determined from the aircraft vertical profiles for summer (left) and winter (right). Whiskers represent the lowest value still within the 1.5 interquartile range (IQR) of the lower quartile and the highest value still within 1.5 IQR of the upper quartile.

face fluxes and atmospheric dynamics in different seasons, the results are separated into summer (April–September) and winter (October–March) half years. As the airborne data used were collected during late morning–early afternoon the figure describes daytime conditions.

Theoretically, a monotone increase of median bias is expected with increasing elevation. The variable internal structure of the PBL and the limited number of data cause the more complex picture seen in Fig. 1. The bottom panels of the figure also show the frequency distribution of the PBL height at 12:00 UTC for the days considered. Comparing the PBL-height statistics of the flight days and those of all days for the period of 2006–2008, the fair-weather bias of the flight days can be noticed, which should be kept in mind while interpreting of the results. Bad weather conditions, usually accompanied by shallow PBL, prevented the aircraft measurements. The number of flights was 56 in summer and 80 in winter half year.

As mentioned in Sect. 2.2., the "value" of the bivariate tower height–estimation height function at any given point in altitude space is a frequency distribution, which cannot be presented in a figure. For practical reasons Fig. 1 shows only the median of the distributions that is a single value per point. The other statistical characteristics of the frequency distributions are also important for the interpretation of the results. To give an impression of the frequency distribution, Fig. 2 shows how accurately a tower of height H estimates the CO_2 mole fraction for mid-PBL elevation. Non-conventionally, for better visualization of the results, the independent variable (height of the tower) is presented on the vertical axes, and the frequency distributions of the bias along the horizontal ones. As it was mentioned earlier, it is assumed that a tower taller than the estimation height (the mid-PBL in this case) always reports the exact concentration below its top. Thus the bias for a tower stretching above the actual mid-PBL elevation is 0. The figure is the expanded horizontal cross section of Fig. 1 at 50 % PBL height. Figure 1 can show only the median values in Fig. 2, while Fig. 2 can show the frequency distribution itself for this selected elevation. It should be noted that Fig. 1 is interpolated for the range between the top of the existing tower (115 m) and the lowest elevation accessible by the aircraft (200–250 m) where no actual measurements are available. For this range there is a gap in Fig. 2.

An empirical cumulative density function of the biases can be calculated for any tower height–estimation height combination. As an example Fig. 3 shows the probability with which a tower of H height estimates the CO_2 mole frac-

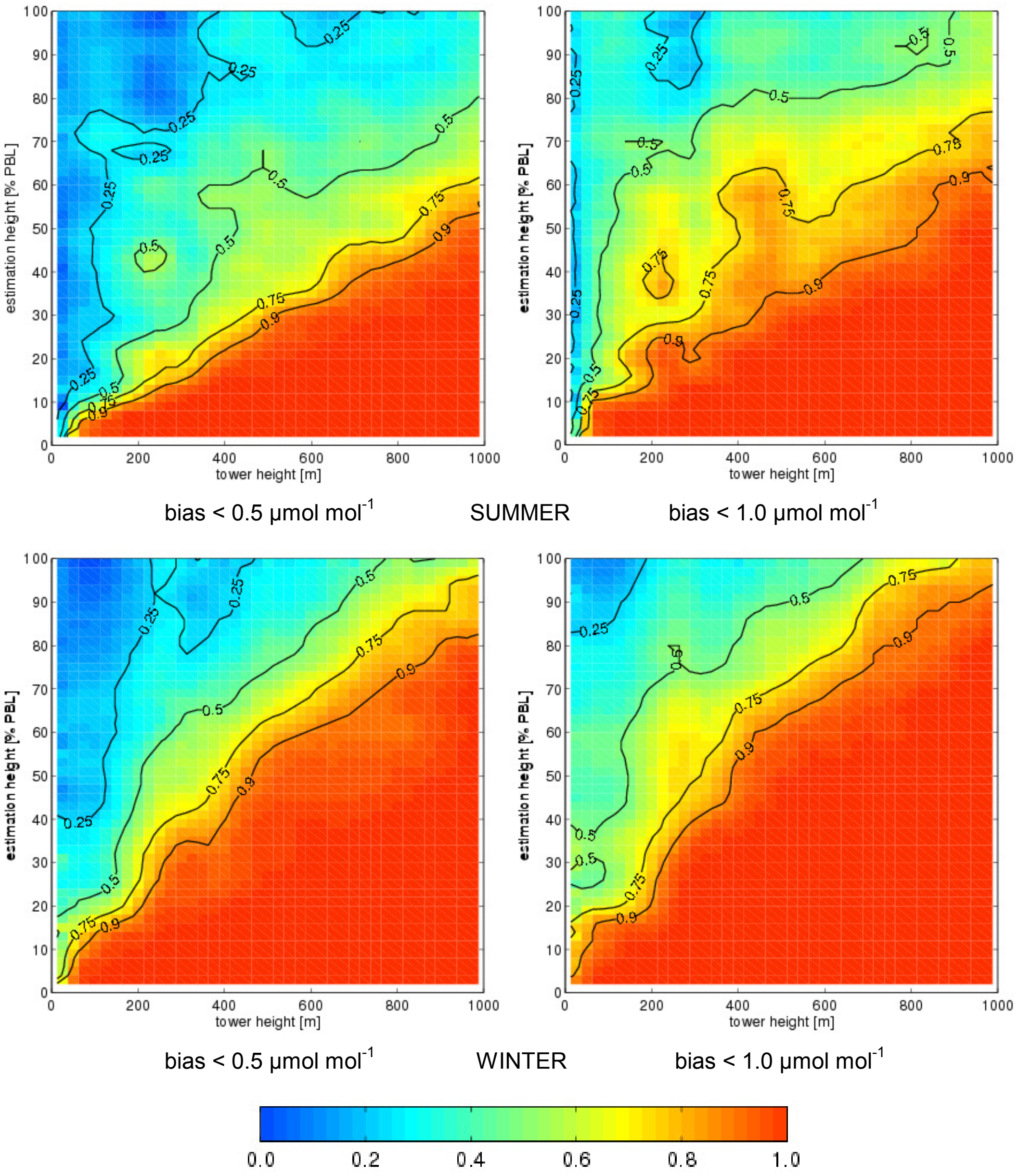

Figure 3. Empirical probability of the cases when the bias between the true CO_2 mole fraction and the estimated (extrapolated) one does not exceed 0.5 (left) or 1.0 µmol mol^{-1} (right) as the function of the height of the hypothetical tower and the estimation height relative to the height of the PBL in summer (top) and winter (bottom).

tion for h elevation relative to the PBL height with accuracy higher than 0.5 µmol mol^{-1} or higher than 1.0 µmol mol^{-1} (bias from the real mole fraction is between -0.5 and $+0.5$ µmol mol^{-1} or between -1.0 and $+1.0$ µmol mol^{-1}, respectively).

3.2 Application of the VTT concept

Tall-tower and airborne measurements revealed that persistence of surface sources/sinks and systematic differences between free-tropospheric and boundary layer mole fractions cause the formation of non-constant vertical CO_2 mole fraction profiles within the PBL (e.g., Font et al., 2008; Haszpra et al., 2012; Sasakawa et al., 2013). Due to the vertical gradients in the mole fractions within the PBL, even in convective conditions, simple vertical extrapolation of a tower measurement (constant profile) unavoidably leads to a bias from the true mole fraction profile. In principle, auxiliary measurements at a tower might improve the estimation of the CO_2 mole fractions within the PBL. In this study, the VTT concept described in Sect. 2.3 is tested to see if its application

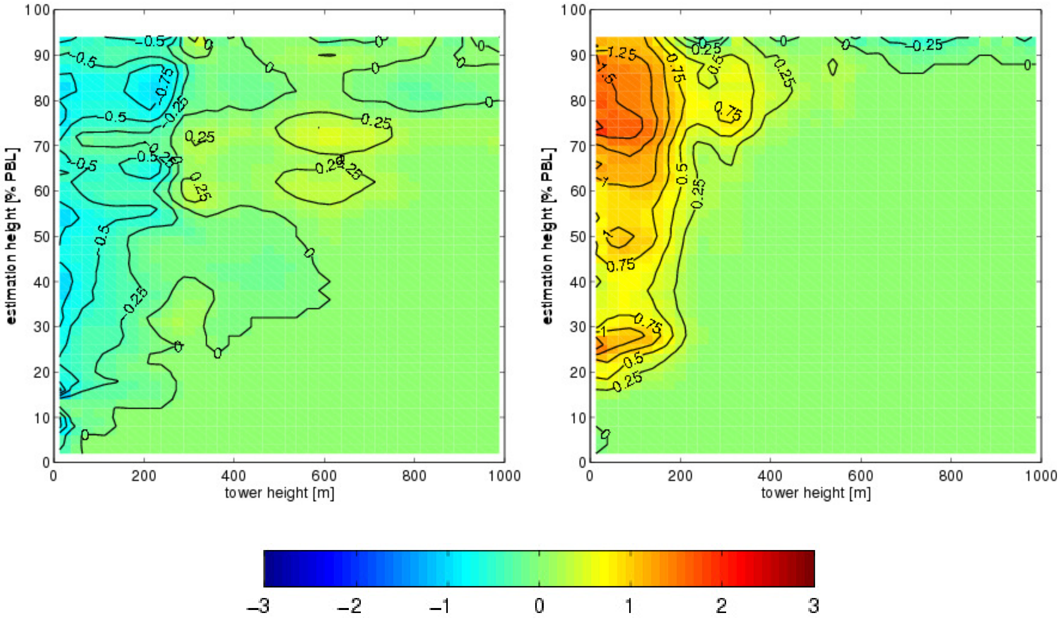

Figure 4. The median bias between the true CO_2 mole fraction and the estimated one using the VTT concept as a function of the height of the hypothetical tower (tower height) simulated by the aircraft or the existing tower and the relative height within the PBL for which the mole fraction is extrapolated (estimation height) from the measurements at the top of the hypothetical tower (µmol mol^{-1}). A negative sign means underestimation by the measurements. Left: summer; right: winter.

could improve the estimation of the vertical distribution of CO_2 mole fraction above the tower in the PBL.

For those cases when the VTT concept could be applied the biases between the measured and estimated CO_2 mole fraction are computed as a function of the tower height and estimation height (expressed in relative PBL height) and shown in Fig. 4 (analogous to Fig. 1). Median biases are calculated only up to 95 % of the PBL (for an explanation see Sect. 2.3). Although the VTT method is only applicable to a subset of the 136 profiles, the 75 profiles (41 in winter and 34 in summer) represent well the complete profile data set.

The gradient functions utilized here are not able to simulate the true vertical mole fraction profile without bias, but Fig. 4 shows that the bias is generally somewhat lower than without the application of the VTT method, especially in summer. Figure 5 shows how much closer our estimated mole fraction gets to the real one if the VTT concept is applied, relative to the simple extrapolation of the tower-top mole fraction (constant profile), again as a function of the tower height and estimation height. A positive sign indicates that the application of the VTT concept improves the estimation of the real vertical distribution of the CO_2 mole fraction, while a negative sign suggests that it is better not to apply the VTT concept. Improvement is calculated as the difference of the absolute values of corresponding median biases with and without the application of the VTT concept. For consistency, in contrast to Figure 1, where all 136 vertical profiles were assessed, here the calculation is based only on those 75 profiles for which the VTT concept could be applied.

Figure 5 shows that improvement can be achieved in both summer and winter, but there are characteristic differences between the seasons.

4 Discussion

4.1 Seasonal differences in the performance of the towers

There are characteristic differences between the plots presented in Fig. 1. In summer (top-left panel in Fig. 1) the shorter the tower, the higher the underestimation of the mole fraction above the tower, especially close to the top of the PBL. Essentially it is caused by two facts: (1) in summer daytime the surface is usually a net CO_2 sink due to the intense photosynthetic CO_2 uptake that exceeds the sum of total ecosystem respiration and anthropogenic sources in this rural region (Barcza, 2001); (2) the upper part of the PBL may be strongly influenced by the entrainment of free-tropospheric air usually having a higher CO_2 mole fraction at this time of the year than the layers below (Haszpra et al., 2012).

In winter (top-right panel in Fig. 1) the shorter the tower, the higher the overestimation of the mole fraction above the tower, especially in the case of shallow PBL. In winter the surface is a net CO_2 source due to the missing or negligible CO_2 uptake by the dormant vegetation, while natural and anthropogenic emissions can accumulate close to the surface due to the weak vertical mixing of the atmo-

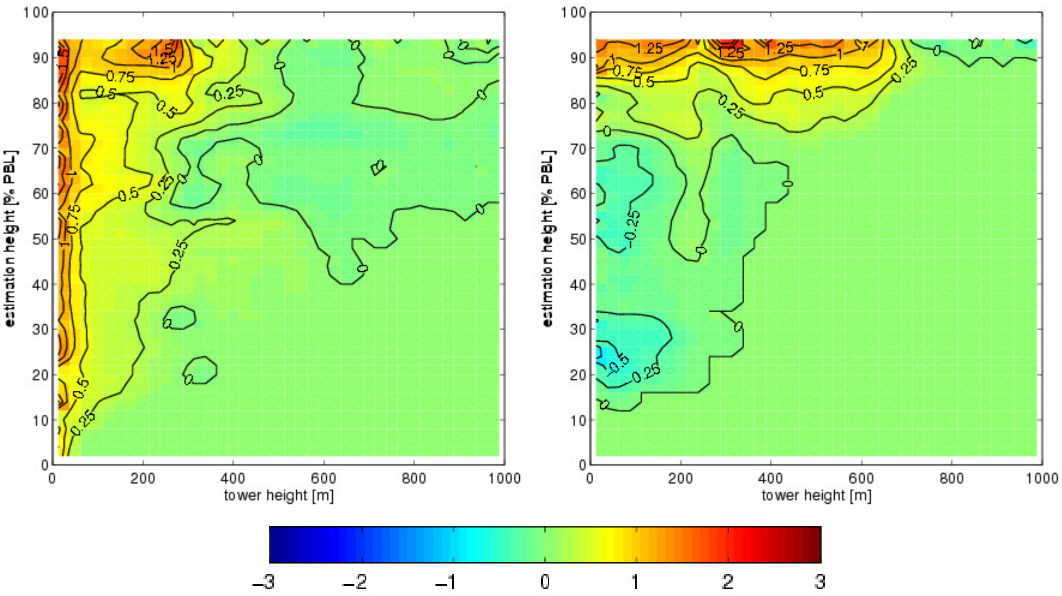

Figure 5. Difference of the median biases of the estimations applying and not applying the VTT concept (µmol mol^{-1}) as a function of the height of the hypothetical tower (tower height) simulated by the aircraft or the existing tower and the relative height within the PBL for which the mole fraction is extrapolated (estimation height) from the measurements at the top of the hypothetical tower. A positive sign indicates that the application of the VTT concept improves the estimation. Left: summer; right: winter.

sphere. Higher vertical gradients, and consequently a higher extrapolation bias, forms under stable stratification, which frequently forms along with shallow PBL in wintertime.

The characteristic differences between the summer and winter half years can also be recognized in Fig. 2. The frequency distribution of the deviation from the mid-PBL mole fraction is rather skewed, especially in the case of short towers. In winter, it has a long right tail (significant overestimation), while in summer it is skewed in the opposite direction. In winter, when the vertical mixing is limited, a high amount of carbon dioxide may accumulate close to the surface. Consequently, short towers sampling the air in this frequently CO$_2$-enriched layer can significantly overestimate mole fractions higher in the PBL (see also the top-right panel in Fig. 1). On the other hand, as the surface is a net CO$_2$ source in this season, usually low-elevation measurements cannot underestimate the CO$_2$ mole fraction aloft in the PBL. In summer daytime, when the vegetation is a net sink, CO$_2$ cannot be accumulated in the lower part of the PBL. Instead, when the vertical mixing is weak, the lower part of the PBL, especially close to the surface, may become CO$_2$-depleted relative to the upper layers. Thus, the measurements performed here tend to underestimate the CO$_2$ mole fraction aloft.

In summer, in the case of surface measurements or short towers the application of the VTT concept improves the CO$_2$ mole fraction estimation for the entire PBL significantly (> 1 µmol mol^{-1}; see left panel in Fig. 5). For towers of up to 250–300 m the improvement is smaller and significant only close to the top of the PBL. For taller towers the application of the VTT concept would not give any advantage. In winter the improvement is considerable only close to the top of the PBL. Within the range of 80–95 % of the PBL height the mean median improvement exceeds 1 µmol mol^{-1} for any tower of reasonable height. There is no improvement for the lower layers of the PBL. This result might be associated with the less intense convection in winter due to the low solar irradiance. It is important to note that the gradient functions were developed for a convective PBL. Development of gradient functions for less convectively dominated conditions could improve the VTT correction for winter conditions.

4.2 How can tall-tower satisfy the requirements?

If we wanted to know the CO$_2$ mole fraction at all times with absolute accuracy (not considering the measurement uncertainty) throughout the PBL, we would need a tower as high as the PBL itself, as well as several air sample inlets along the tower. This is technically and economically not feasible. However, any other demand on the performance of a tower, such as how accurately it should estimate the CO$_2$ mole fraction aloft, would be arbitrary and may be arguable. As a possible approach, criteria may be set for the maximum mean bias or for the maximum median bias not to be exceeded by the tower-top measurements up to a given elevation or for the probability with which the bias should be below a given limit.

Given a criterion for the maximum median bias, the minimum height of the tower satisfying the criterion can be determined. Figure 1 shows what is possible without the application of the VTT method. The detailed data behind Fig. 1 (see the Supplement) show that a median bias lower than 0.5 µmol mol^{-1} can be achieved up to the middle of the PBL by a tower of 170–180 m height in summer daytime. A tower of about 330 m height can provide this accuracy up to the top of the PBL without any auxiliary measurement. More common towers of 100–250 m can estimate the CO_2 mole fraction with a median (negative) bias < 1 µmol mol^{-1} up to about 75 % of the PBL.

A 170–180 m tall tower can also estimate the CO_2 mole fraction at the mid-PBL with a median bias of less than 0.5 µmol mol^{-1} in winter. However, this good performance is due to the usually shallow PBL, for which a tower of 170–180 m height is relatively tall. Otherwise, due to the usually weak atmospheric mixing and the resultant high vertical concentration gradient, the tower measurements cannot be extrapolated much higher in the atmosphere with a low bias than the elevation of the measurements themselves.

The chaotic nature of the atmosphere, the vertical mixing variable in both time and space and the ever-changing advection keep the planetary boundary layer heterogeneous even if it is usually considered “well mixed” (Stoy et al., 2013). As a result, the deviations of the measurements at a given elevation from another one scatter in a wide range, as could be seen in Fig. 2. Figure 3 shows the probability with which the bias remains below a given accuracy demand as a function of the height of the tower.

If we aspired after mid-PBL CO_2 mole fraction estimations with a maximum bias of 0.5 µmol mol^{-1} in 75 % of the cases in summer, we would need an unrealistically tall tower of 825–850 m. Taking into account the typical range of the summer daytime PBL height at Hegyhátsál (1400–2000 m), Fig. 3 suggests that highly reliable vertical extrapolation of the tower measurements (< 0.5 µmol mol^{-1} bias at 75 % probability) is hardly possible. If we are satisfied by 1 µmol mol^{-1} with 75 % probability, a tower of around 400 m height will do. If we are less ambitious, and accept that the bias exceeds 1 µmol mol^{-1} in half of the cases, then any tall tower (> 100 m) can fulfill the requirement. The common tall towers of 100–300 m height used for CO_2 monitoring can provide < 1 µmol mol^{-1} bias with 50 % probability up to 60–75 % of the PBL height.

In winter, due to the shallower PBL, 1 µmol mol^{-1} maximum bias with 75 % probability at mid-PBL would require a tower of only about 300 m height. However, usually shorter towers perform worse in summer. Variable accumulation of CO_2 in the surface layer results in a wide range of extrapolation bias higher up above the tower (see, e.g., Fig. 2), and so the probability of a bias in the ±1 µmol mol^{-1} range is relatively low.

Applying the VTT method, even with imperfect gradient functions, reduces the bias considerably. The lower-than-0.5 µmol mol^{-1} median bias can be achieved up to the middle of the PBL by a tower of only about 100 m height when applying the VTT concept in summer daytime (Fig. 4), only a little taller than the half of that not applying the VTT method. If a CO_2 mole fraction median (negative) bias of < 1 µmol mol^{-1} is acceptable, then even the surface measurements (∼ 10 m) can satisfy the requirement up to 95 % of the PBL, assuming that the VTT concept is applied.

In winter, the application of the VTT concept does not help much except for the top region of the PBL, as can be seen in the right panel in Fig. 5. The reason for the better estimation of the upper PBL mole fraction is that the VTT model handles the free-tropospheric entrainment, which may influence the mole fraction here significantly due to the frequently large CO_2 mole fraction jump at the top of the PBL.

Generally, the VTT concept improves the performance of the relative short towers (Fig. 5). Tall towers with a height of 400–800 m required for low maximum bias at high probability do not perform better when applying the VTT method. However, the more common towers of 100–300 m can provide < 1 µmol mol^{-1} bias with 50 % probability up to about 80 % of the PBL height (Fig. 6), 5–20 percentage points higher than without the VTT method. This performance could be improved even further with continued study of the PBL gradient functions. The existing functions are the most suitable for convective conditions. Gradient function estimates with more observational sites in different environment would improve our quantification of flux–gradient relationships in the PBL.

4.3 Performance of common tall towers

Usually scientists are not in the position to construct monitoring towers according to theoretical accuracy criteria. In most cases existing meteorological or telecommunication towers can be equipped with CO_2 (and other) monitors. There are very few instrumented towers in the world reaching 300–500 m (http://www.esrl.noaa.gov/gmd/ccgg/towers/). Most of the towers used for GHG monitoring are only 100–300 m tall (http://www.esrl.noaa.gov/gmd/ccgg/towers/; Vermeulen, 2007; Andrews et al., 2013). Figures 1–6 also help to estimate what we can expect from the existing or potentially available monitoring towers. In the pan-European GHG monitoring network ICOS (http://www.icos-infrastructure.eu/home) the tall-tower sites have a tower of at least 100 m tall. A 100 m tall atmospheric monitoring tower, similar to that at Hegyhátsál (115 m), can estimate the daytime CO_2 mole fraction within 0.8 µmol mol^{-1} median bias up to the middle of the PBL and with a < 1 µmol mol^{-1} median underestimation up to 75 % of the PBL height in summer. The median underestimation applying the VTT concept is about 0.5 µmol mol^{-1} for the whole range of 50–75 % of the PBL. At mid-PBL the bias is < 1 µmol mol^{-1} in half of the cases if the VTT concept is not applied, and the probability does not increase much if it is applied.

In winter the tower can estimate the daytime CO_2 mole fraction at mid-PBL with +1 µmol mol^{-1} median bias. The bias is higher at this elevation in ∼ 55 % of the cases. Over-

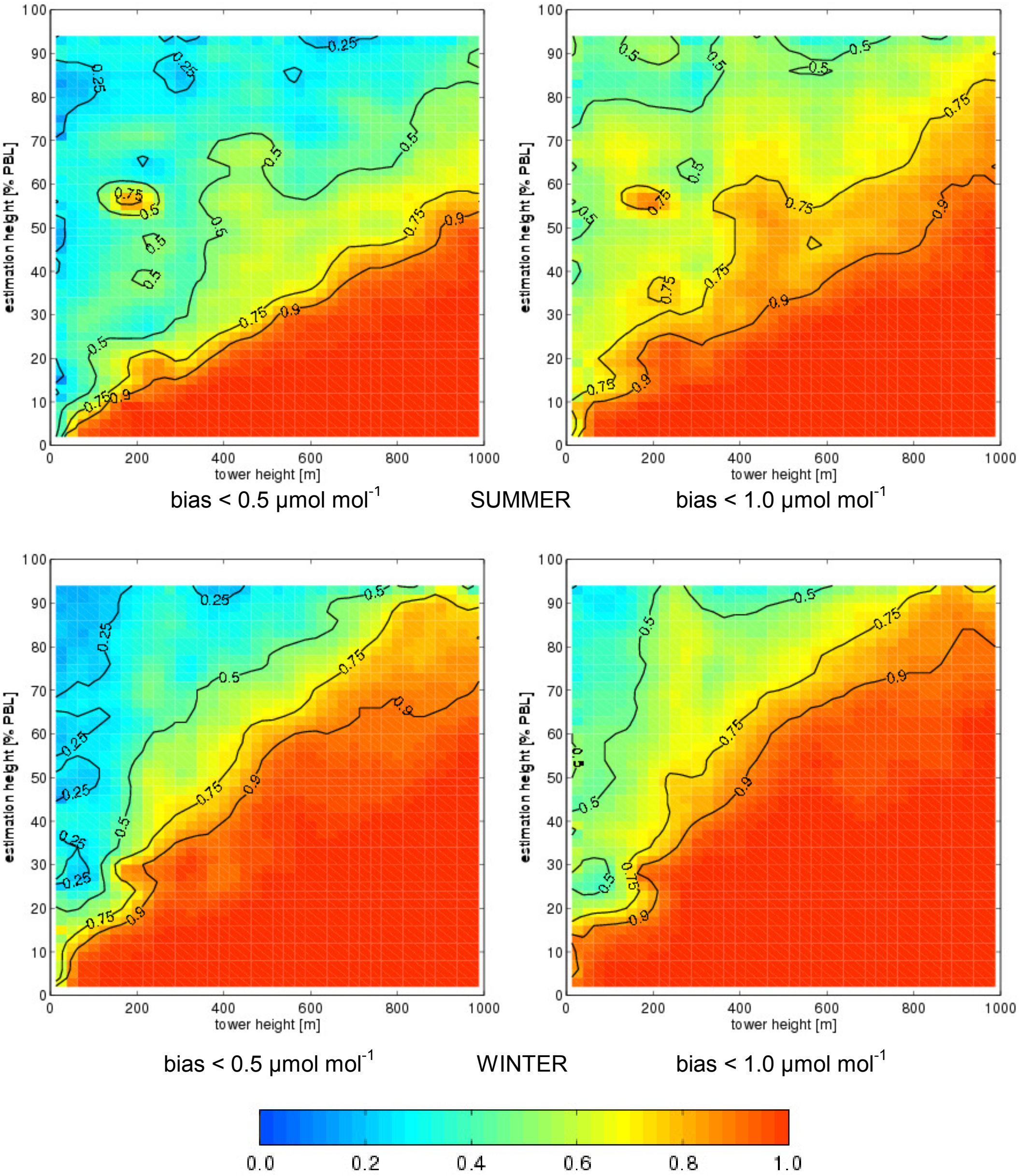

Figure 6. Empirical probability of the cases when the bias between the true CO_2 mole fraction and the estimated one does not exceed 0.5 (left) or 1.0 µmol mol^{-1} (right) at the application of the VTT concept as the function of the height of the hypothetical tower and the estimation height relative to the height of the PBL in summer (top) and winter (bottom).

estimation quickly increases with elevation (top-right panel in Fig. 1). If the VTT method is used, the median overestimation at the middle of the PBL is rather similar and the probability is better only with a few percentage points.

For taller tower of 200–300 m the improvement is smaller (summer) or negligible (winter, Fig. 5).

In addition to the tall towers there are also ground-based monitoring stations in the GHG monitoring networks. Typically they sample air at 5–20 m elevation above the ground. According to our study these stations can estimate the daytime mid-PBL CO_2 mole fraction with an accuracy of 3.7/4.2 µmol mol^{-1} (summer/winter) with a probability of 75 % (2.1/1.2 µmol mol^{-1} with a probability of 50 %) and with a median value of −2.1/+1.2 µmol mol^{-1}. The application of the VTT concept improves the mid-PBL mole fraction estimations to 2.2/2.2 µmol mol^{-1} (summer/winter) with a probability of 75 % (1.1/1.1 µmol mol^{-1} with a probability of 50 %) and with a median value of −0.8/+0.8 µmol mol^{-1}. Although towers of limited height cannot represent the PBL as well as the taller ones, they are highly valuable in inversion estimates (Lauvaux et al., 2012; Schuh et al., 2013).

4.4 Advantage of the application of the VTT concept

As shown in Fig. 5, the VTT method providing theoretical information on the vertical gradient of the CO_2 mole fraction in the PBL may improve the PBL concentration estimates. The shorter the tower, the more remarkable the improvement is in summer. In the case of CO_2 mole fraction monitoring close to the surface, the VTT method may improve the vertical profile estimation by $\sim 1.2\,\mu\text{mol}\,\text{mol}^{-1}$ almost up to the top of the PBL, relative to the simple extrapolation of the surface measurements. In the case of towers of 100–300 m height the improvement is lower but still substantial, especially in the upper PBL. In winter, as a consequence of the weak vertical mixing of the lower atmosphere and small NEE, the application of the VTT concept cannot help much, although significant improvement can be achieved close to the top of the PBL due to the inclusion of the free-tropospheric entrainment into the profile estimation.

Applicability of the VTT concept requires sensible heat and CO_2 vertical flux measurements by an eddy covariance system. In addition to the better estimation of CO_2 vertical distribution in the PBL, installation of an EC system on a tall tower also helps to map the biosphere–atmosphere CO_2 exchange of an extended region that may be covered by a characteristic mix of ecological systems (Barcza et al., 2009).

As a test of the theoretical considerations on the height above the ground of the eddy covariance system, the calculations were repeated using the available data set of another eddy covariance system located 3 m above the grass-covered ground at the bottom of the Hegyhátsál tall tower (Barcza, 2001; Nagy et al., 2011). Although the overlapping operation time of the two systems (82 and 3 m) was too short to draw a sound conclusion, we got comparable results. This is most likely caused by the covariance of NEE and sensible heat flux between the low- and high-elevation eddy covariance systems. Covariance of NEE is the result of the fact that the functioning of both the mixed croplands sampled by the high-elevation eddy covariance system and the grassland sampled by the low-elevation one is driven by the same environmental factors (radiation, temperature, precipitation). Due to footprint considerations, we recommend using the highest-possible elevation for the eddy covariance measurements.

5 Concluding remarks

In the present study we analyzed how well towers of different heights could estimate the vertical distribution of CO_2 in the PBL. The information may improve the integration of tower mole fraction observations into atmospheric models since many modeling systems cannot accurately reproduce the vertical gradients in the atmospheric surface layer.

Our results are primarily valid for relatively homogeneous, flat regions. The data in this study reflect only the daytime conditions. The nighttime boundary layer is typically shallower over a continental site than the daytime PBL and is often stably stratified, making it difficult to simulate in transport models. On 70 % of the nights (00:00 UTC) at the Hegyhátsál tall-tower greenhouse gas monitoring station, the base of the present study, the height of the PBL is below 200 m according to the MARS database of ECMWF. A tower satisfying the daytime requirements may encompass the entire nocturnal PBL and provide a directly measured, PBL-integrated mole fraction if CO_2 is measured at multiple heights. It should be noted that the spatial representativeness of the nighttime measurements is rather low because of the limited mixing. They mostly represent only the local conditions (Haszpra, 1999).

As was shown, application of the VTT concept may improve the performance of the shorter tower, especially in summer. The extra benefit of the operation of an EC system is the information on the local biosphere–atmosphere carbon budget. Technological development in recent years has also made the EC flux measurement of certain non-CO_2 GHG (CH_4, N_2O) possible; therefore the VTT concept can be extended beyond CO_2 measurements. More observations of flux and mole fraction profiles will enable improved determination of the PBL gradient functions.

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