Biogeosciences Discuss., 10, 15337–15372, 2013
www.biogeosciences-discuss.net/10/15337/2013/
doi:10.5194/bgd-10-15337-2013

Biogeosciences Discussions
Open Access

Inferences from CO_2 and CH_4 concentration profiles at the Zotino Tall Tower Observatory (ZOTTO) on local summer-time ecosystem fluxes

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Received: 30 August 2013 – Accepted: 9 September 2013 – Published: 23 September 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The Siberian region is still sparsely covered by ecosystem observatories, which motivates to exploit existing datasets to gain spatially and temporally better-resolved carbon fluxes. The Zotino Tall Tower Observatory (ZOTTO, 60°48′ N, 89°21′ E) observations of CO_2 and CH_4 mole fractions as well as meteorological parameters from six different heights up to 301 m allow for an additional estimate of surface-atmosphere fluxes of CO_2 and CH_4 for the Middle-Siberian region since 2009. The total carbon flux is calculated from the storage and the turbulent flux component. The gradients between the different tower levels determine the storage flux component, which dominates the local fluxes, especially during night. As a correction term, the turbulent flux component was estimated by the modified Bowen ratio method based on the sensible heat flux measurements at the top of the tower. The gained average night time fluxes (23:00 to 04:00 local time) are $2.7 \pm 1.1\,\mu mol\,(m^2\,s)^{-1}$ for CO_2 and $5.6 \pm 4.5\,nmol\,(m^2\,s)^{-1}$ for CH_4 during the summer months June-September in 2009 and 2011. During day, the method is limited due to numeric instabilities from vanishing vertical gradients; however, the derived CO_2 fluxes exhibit reasonable diurnal shape and magnitude compared to the eddy covariance technique, which become available at the site in 2012. Therefore, the tall tower data facilitates the extension of the new eddy covariance flux dataset back in time. The diurnal signal of the CH_4 flux is predominantly characterized by a strong morning transition, which is explained by local topographic effects.

1 Introduction

1.1 Tall tower concept for Siberia

The increase of greenhouse gas concentrations (mainly CO_2 and CH_4) drives changes in the global climate (IPCC, 2007). For the understanding of the underlying global carbon cycle, it is important to describe the boreal region with its large carbon stocks and to quantify its exchange fluxes between ecosystems and the atmosphere.

The atmosphere can be seen as a natural integrator of the surface-atmosphere exchange. Signals from local pollutions become more diluted with increasing height above ground. Hence, the atmospheric data from a larger height represent an averaged signal from a larger area, and atmospheric mole fraction measurements were preferably installed on very tall towers (> 200 m) (Bakwin et al., 1998; Haszpra et al., 2001; Vermeulen, 2007). Transport inversion modeling approaches make use of these concentration measurements to estimate surface-atmosphere fluxes on global scale (Rödenbeck et al., 2003; Bergamaschi et al., 2009). For a better understanding of the Siberian carbon cycle, the Zotino Tall Tower Observatory (ZOTTO) was built in Central Siberia in 2006. In the following years, the observation network also grew in the western Siberian lowlands (Arshinov et al., 2009), which allowed first flux estimates with transport inversion models on regional scale (Winderlich, 2012; Saeki et al., 2013).

1.2 Local flux estimation techniques

The observation of the atmospheric gas composition is one method among several others to gain information about the carbon fluxes. The eddy covariance technique allows direct carbon flux measurements through the high frequency observations of atmospheric turbulences. But while several tens of stations are in service in the North American boreal zone, the Siberian region is only sparsely covered by those measurements (www.fluxnet.ornl.gov) (Mizoguchi et al., 2009). In the Asian boreal forest region, CO_2 flux measurement sites were established in Yakutsk, Zotino (Heimann, 2005), and Tura (Nakai et al., 2008) in the 1990ies. But most of them are not in service any more, e.g. the eddy covariance measurements in the vicinity of ZOTTO were operated from 1996 until 2004 (Schulze et al., 1999; Valentini et al., 2000). The measurement of CH_4 fluxes with the eddy covariance technique is also principally available (e.g. Shurpali and Verma, 1998), but it is used even rarer; the first complete annual cycle was recorded

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only recently (Rinne et al., 2007). In Siberia, the predominant way to determine CH_4 fluxes is the chamber measurement.

The rather small area of 1 km^2 represented by the eddy covariance technique (Davis et al., 2003) can be expanded by using boundary layer budget methods, where temporal changes in concentration differences between the bottom layer and the overlaying free troposphere are used to estimate ecosystem fluxes on regional scale with footprint areas of 10^4–10^6 km^2 (Helliker et al., 2004; Bakwin et al., 2004). Such a method applied to aircraft profile measurements over the ZOTTO site provided CO_2 flux estimates of −3.3 to −9.6 µmol $(m^2\,s)^{-1}$ for two summer days in 1996, but associated uncertainties ranged up to 11.8 µmol $(m^2\,s)^{-1}$ due to unknown entrainment fluxes (Lloyd et al., 2001).

Eddy covariance techniques, data from the free troposphere, and mixing ratio measurements on several tall tower levels can also be combined for better information on regional ecosystem fluxes (Wang et al., 2007; Chen et al., 2007; Davis et al., 2003; Haszpra et al., 2005) . Similarly, we make use of the Zotino tall tower data from different heights to estimate ecosystem fluxes on intermediate scales ($\sim 10^4$ km^2).

1.3 The ZOTTO site

The Zotino Tall Tower Observatory (ZOTTO) is located at 60°48′ N, 89°21′ E (114 m a.s.l.), approximately 20 km west of Zotino village at the Yenisei River. The surrounding area is characterized by gentle hills of 60–130 m height a.s.l. covered with light taiga forests (Pinus sylvestris dominated) on lichen covered sandy soils (Schulze et al., 2002). Higher elevations of up to 500 m a.s.l. exist about 100 km east of the station. The nearest airport is 90 km north in Bor (2600 inhabitants), the closest cities are Yeniseysk and Lesosibirsk (20 000 and 61 000 inh.) in south-south-eastern direction, more than 300 km away, and Krasnoyarsk (1 Mio. inh.) about 600 km south of ZOTTO.

At the ZOTTO site, the greenhouse gas concentrations of CO_2, CH_4, and H_2O, and meteorological data are recorded at 6 height levels (4 m, 52 m, 92 m, 164 m, 227 m, 301 m a.g.l.) since 2009 (Winderlich et al., 2010). Each of the six tower-inlets is contin-

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uously flushed through 8 L buffer volumes. The result is a time-integrated signal with a mixing time of 37 min for each line. This is long enough to switch between all height-levels and assure a quasi-continuous data record from all six heights with only one analyzer. Additionally, all the tower is equipped with six 3-D sonic anemometers for 3-dimensional wind measurement, with temperature, humidity and pressure (see Supplement in Winderlich et al., 2010).

In June 2012, two eddy covariance towers started operation nearby the ZOTTO site. One is located 900 m in north-north-eastern direction in the pine forest; the other is located 3 km in north-eastern direction in a bog. Both towers are equipped with an enclosed CO_2 / H_2O gas analyzer (LI-7200, LI-COR Inc., USA), an 3-D ultrasonic-anemometer (USA-1, METEK GmbH, Germany), meteorological sensors (temperature, humidity, radiation) and dataloggers (CR3000 and CR10X, Campbell Scientific Inc., USA). The bog tower also includes a CH_4 eddy covariance gas analyzer (G1301-f, Picarro Inc, USA), which is not yet reporting data in 2012 due to an early operation failure and national restrictions that complicated an immediate repair.

Since the Siberian region is still sparsely covered by ecosystem observatories, it is important to thoroughly exploit the existing datasets for spatially and temporally better resolved fluxes. Therefore, we explore in this paper how much information on local carbon fluxes can be extracted from the CO_2 and CH_4 concentration profile along the 301 m tall ZOTTO station since 2009. We will make use of heat flux and vertical wind measurements for the analysis of our dataset. This may eventually allow us to extent the newly installed eddy covariance flux dataset back in time. In turn, this eddy covariance dataset is also used to evaluate the quality of our estimates for the year 2012.

2 Methods

2.1 Flux estimates from tower profiles

This chapter gives an overview of how the meteorological measurement allows us to assess surface-atmosphere exchange fluxes for CO_2 and CH_4 at intermediate scales. Generally, the net ecosystem exchange (NEE) in a volume with the height z_r can be calculated as the sum of storage flux, turbulent Eddy flux, and advection flux (Aubinet et al., 2005; Feigenwinter et al., 2008; Yi et al., 2000):

$$\mathrm{NEE} = F_{\mathrm{Stor}} + F_{\mathrm{Eddy}} + F_{\mathrm{adv}} = \int_0^{z_r} \frac{1}{V_m} \cdot \frac{\partial \bar{c}}{\partial t} \mathrm{d}z + \frac{1}{V_m} \cdot \overline{w'c'}(z_r) + \ldots, \tag{1}$$

where w is the wind component vertical z direction, c is the concentration of the observed gas (with 30 min mean $\bar{c}$ and its deviation c' from the mean; Reynolds averaging) and the molar volume is $V_m(z) = M_{\mathrm{Air}}/\rho_{\mathrm{Air}}(z)$. The sign convention used here gives positive NEE for ecosystem emissions, where a positive flux term (= source) corresponds to a transport out of the control volume (Feigenwinter et al., 2004).

The first two terms are discussed in detail in the subsequent subsections. The advection term is heavily site dependent and mainly influenced by topography or land cover heterogeneity induced breezes (Feigenwinter et al., 2008; Feigenwinter et al., 2004; Aubinet et al., 2005; Aubinet, 2008; Aubinet et al., 2010; Yi et al., 2000). Particularly during the morning hours, comparisons of NEE measurements on different tall tower levels suggest that advection can dominate the total flux; at a 447 m tall tower the impact of total advection was estimated to be about 10 % of the overall flux (Yi et al., 2000). These vertical advection components are likely to be compensated by the horizontal advection. As there is no well-calibrated information about the horizontal distribution of CO_2 and CH_4, it is impossible to judge on the contribution of horizontal advection to the measurement signal. Since including only one term in the total flux estimate would make it even worse than using none (Finnigan, 1999), we finally omit contributions from advection in our flux estimates. Note that they have been disregarded in other studies as well (Haszpra et al., 2005).

All calculations are done with a temporal resolution of 30 min. The time is given for the Krasnoyarsk time zone (KRAT = UTC + 7 h), which is shifted by one hour compared to local solar time (LOC = KRAT – 1 h). Please note, that official Krasnoyarsk time zone changed to permanent daylight saving time (UTC + 8 h) in March 2011, which is ignored for a homogeneous data analysis. The final total flux estimates are shown as monthly averages. As a side effect, synoptic events such as front passages (Hurwitz et al., 2004) are averaged out and advection is assumed to get negligible (Davis et al., 2003).

2.1.1 Storage flux

The storage term F_{Stor} in equation (1) describes the amount of carbon that is accumulated over time below the observation height z. For illustration, the diurnal development of the CO_2 profile along the tower is given in Fig. 1. During night, radiation cools the ground and consequently the lower air layers. Hence, a stratified nocturnal boundary layer emerges and accumulates all gases that are emitted from the surface. With sunrise two processes start: (1) heat drives turbulent transport of CO_2 enriched air parcels upward, and (2) photosynthesis assimilates the CO_2 close to the ground. At noon, the atmosphere is well mixed, photosynthesis reduces the CO_2 concentration at all heights.

According to Eq. (1), the storage flux can be visualized through trapezoidal areas between the half-hourly time steps t_i and t_{i+1}, and the different tower heights (see Fig. 1, grey shaded area). It adds up to:

$$F_{\mathrm{Stor}}(t_i, z_h) = \int_{z_{h+1}}^{z_h} \frac{1}{V_{\mathrm{m}}} \cdot \frac{\partial \bar{c}(t_i)}{\partial t} \mathrm{d}z = \int_{z_{h+1}}^{z_h} \frac{\rho_{\mathrm{Air}}(z)}{M_{\mathrm{Air}}} \cdot \frac{\partial \bar{c}(t_i)}{\partial t} \mathrm{d}z \qquad (2)$$

$$\cong \sum_{h=1}^{5} \frac{\frac{1}{2}(\rho_h + \rho_{h+1})}{28.9644\,\mathrm{g\,mol^{-1}}} \cdot \frac{\frac{1}{2}((c_h(t_{i+1}) - c_h(t_i)) + (c_{h+1}(t_{i+1}) - c_{h+1}(t_i)))}{t_{i+1} - t_i} \cdot (z_h - z_{h+1})$$

with the air density ρ, mixing ratio c, and height z. The index $h = 1 \ldots 6$ describes the tower levels ($z_1 = 301$ m, ...), index i marks the different time steps. To cover the full tower height, the storage flux terms between all heights are summed up and the mixing ratio below 4 m level is assumed constant.

The storage flux F_{Stor} reaches its maximum during night from 23:00 to 4.00 a.m., before atmospheric mixing starts again. However, the varying concentration at the 301 m level (Fig. 1) indicates that some CO_2 escapes aloft through another flux component. We try to capture this flux beyond 301 m by including the turbulent flux term. This is the opposite approach to the eddy covariance technique, which detects the turbulent flux mainly and requires the storage flux as an important correction term especially during night and under low turbulence conditions (see Fig. 5.2 in Aubinet et al., 2012). Thus, the flux estimates derived by our method tends to be most reliable when fluxes measured by the eddy covariance method are least and vice versa.

2.1.2 Turbulent flux

The carbon flux of ecosystems is commonly detected by the eddy covariance method. The underlying essential condition is a wind and gas concentration measurement at high frequency (~5–40 Hz). Restricted by the measurement frequency of our CO_2 / CH_4 analyzer (0.2 Hz), the long tubing (up to 320 m), and the deployment of buffer volumes (mixing time ~40 min ~0.0004 Hz) our data does not allow direct eddy flux measurements F_{Eddy} at the tall tower.

Several alternative methods for flux detection are presented in the literature (Businger, 1986; Moncrieff et al., 1997; Verma, 1990). Following these approaches, we assume that turbulent eddies act similar to molecular diffusion and distribute proportional to the vertical concentration gradient. By introducing the eddy diffusivity K_C it can be written:

$$F_{\text{Eddy}} \cdot V_{\text{m}} = \overline{w'c'} = K_C \frac{\text{d}c}{\text{d}z} \quad (3)$$

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Following the similarity theory, we presume the same turbulent exchange coefficients for heat, water vapor, and other trace gases. Thus, we can make use of the sensible heat flux measurements H at all heights at ZOTTO. H is related to the potential temperature gradient $\mathrm{d}T_{\mathrm{pot}}/\mathrm{d}z$:

$$H = \rho_{\mathrm{Air}} C_P K_T \frac{\mathrm{d}T_{\mathrm{pot}}}{\mathrm{d}z} \tag{4}$$

Similarity for gas and heat implies $K_C = K_T$. The combination of Eqs. (3) and (4) and following the "modified Bowen ratio method" (Businger, 1986) obtains:

$$F_{\mathrm{Eddy}} = \frac{H}{C_p \cdot M_{\mathrm{Air}}} \frac{\partial c/\partial z}{\partial T_{\mathrm{pot}}/\partial z} \tag{5}$$

The concentration and temperature gradients between two adjacent tower heights are used to compute the turbulent fluxes at five intermediate levels (28 m, 72 m, 125 m, 193 m, 264 m).

Our approach has certain limitations. Models show a dissimilarity between heat and CO_2 fluxes: while the CO_2 flux stays approximately constant with height, the heat flux linearly decreases up to the boundary layer height; however, the Eddy diffusivities of heat and CO_2 are almost the same (Huang et al., 2009). Measurements over grass covered level terrain also showed a fixed 1 : 1 relationship of the eddy diffusivities K_C and K_q for stable and unstable conditions (Park et al., 2009). However, advection can alter the signal especially during sunrise or sunset (Verma et al., 1978).

The measurement uncertainty is another restriction for our turbulent flux estimates. The ratio of two noisy signals can result in unreasonably large numbers, e.g. when dividing by a potential temperature difference close to zero. Instead of excluding fluxes that exceed certain thresholds, we propagate the errors of the measurement ($\Delta CO_2 = 0.05$ ppm, $\Delta CH_4 = 2$ ppb, $\Delta\mathrm{Temp} = 0.3$ K, $\Delta H/H = 10\,\%$, $\Delta z = 1$ m) and omit 30 min eddy turbulence flux data points when the error exceeds 500 µmol $(\mathrm{m}^2\,\mathrm{s})^{-1}$ and 5000 nmol $(\mathrm{m}^2\,\mathrm{s})^{-1}$ for CO_2 and CH_4, respectively.

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In summary, the modified Bowen ratio method can give only limited information about the turbulent fluxes; hence, the storage flux is our most reliable flux component. The 301 m height of the ZOTTO tower is sufficient to capture most of the NEE as storage flux already, at least during night, leaving the eddy flux data as a small correction term. We use the sum of the storage flux and the eddy flux component at the highest level as the best and the most robust flux estimate we can get with the available data streams.

Our study is limited to the summer data, because the strong icing of the wind sensors (despite heating) prevents analysis for the winter months. Fortunately, the ecosystem signals are dominated by the summer and are generally weak during winter.

2.2 Fluxes from eddy covariance towers

The eddy covariance systems that are available as an independent data stream since summer 2012 (see Sect. 1.3) are routinely analyzed with the software EddySoft (Kolle and Rebmann, 2007). The covariance tower in the bog measures the turbulent fluxes at 9 m height. The tower in the forest stand is equipped with eddy covariance technique at 30 m height, and additionally detects the CO_2 profile at 9 height levels (0.1 m, 0.3 m, 1.0 m, 2.0 m, 5.0 m, 9.0 m, 15.0 m, 22.0 m, 30.0 m) to correct for the storage flux component.

2.3 Footprint

To attribute the measurement signals correctly to the original emission area, it is crucial to understand the different pathways of the analyzed air parcels, e.g. from the polar region, Europe or the nearby Central Siberian area (Paris et al., 2010; Eneroth et al., 2003). We use the Lagrangian transport model STILT (Lin et al., 2003), which is driven by ECMWF meteorology, for an overview of the origin of air parcels arriving at ZOTTO.

As the storage flux drives our total flux estimates predominantly during night, we calculated the average nocturnal footprint of the 301 m tower level in Fig. 2. The storage fluxes are driven by concentration differences that mainly built up from 11.00 p.m. to

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5.00 a.m. next morning (compare Fig. 1), which determines the limits of our backwards STILT calculations. As a result, the fluxes of the surrounding boreal forests in the West Siberian plain and to some extent the Central Siberian plateau have the largest impact on the measurement signal. The area that contributes to the local storage flux signal covers 35 000 km^2, 99 % of the signal arrives from within 250 km, half of the cumulated surface influence signal originates from a distance less than 90 km.

The footprint of a concentration measurement differs from this of a direct turbulent flux measurement (Schmid, 1994, chapter 8.2.4 in Aubinet et al., 2012). While the concentration measurement sums up all emissions along the particle's back trajectory, a flux footprint follows an air parcel until the turbulence eddy touches the ground. For our eddy covariance towers, we can follow the standard approach with a surface-layer flux models. We follow Schuepp et al. (1990) to estimate the flux footprints for the two flux towers with 30 m height in the forest and 9 m height in the bog from static parameters (e.g. height above ground) and meteorological data (e.g. friction velocity u^*). Thus, our software EddySoft (Kolle and Rebmann, 2007) computes the average 90 % fetch with 1.3 km for the bog, and 1.7 km for the forest. Therefore, the two towers represent well their surrounding local ecosystems.

3 Results and discussion

3.1 Tall tower profiles

The basis for our flux estimates are the mean diurnal cycles of CO_2 and CH_4 profiles, shown in Figs. 3 and 4 for the individual summer months from 2009 to 2012. During night, the emitted gases are trapped in the nocturnal boundary layer close to the ground. The lowest 4 m level experiences the strongest concentration increase, but even the 301 m level is partially influenced by nocturnal boundary layer air. During day, the atmosphere becomes well-mixed and the gas concentrations become nearly indistinguishable at the different height levels (compare discussion to Fig. 1).

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The diurnal behavior of the CO_2 and CH_4 profiles are driven by the diurnal variation of the boundary layer, which can be illustrated with the potential temperature distribution in Fig. 5. At night, the temperatures increase with height, a sign for a very stable layering of the nocturnal boundary layer, a temperature inversion. During day, potential temperatures on all heights adjust to a common temperature; the boundary layer is well-mixed.

The capping nighttime inversion causes an amplitude in the nocturnal CO_2 signal at ZOTTO (Fig. 3) that is comparable to the one measured at other tall towers e.g. in Europe (Popa et al., 2010; Vermeulen et al., 2011). In contrast, CH_4 has a more intense diurnal cycle at ZOTTO than a European rural site (Popa et al., 2010); larger contributions are also expected from the Siberian wetlands.

Table 1 gives an overview of the climatic conditions during the four years. In 2010, the weather was quite cold with the least sunshine (as reflected by the lower average photosynthetically active radiation). The induced decline in biospheric activity is reflected in the weaker diurnal cycles of CO_2 and CH_4 in Figs. 3 and 4. In 2012, the year with the driest and warmest summer, the ecosystem is disturbed by strong forest fires that dominated the whole Middle-Siberian region almost for the full summer season. The fires came as close as 10 km to the station in July 2012. The heavy smoke plumes limited the visibility around the station, and the heavy aerosol load made frequent changes of the inlet filters unavoidable.

3.2 CO_2 fluxes

Before analyzing our flux estimates, we check for the influence of local pollution through the diesel power generators, which are located about 150 m southeast of the tower, and may alter our CO_2 measurement. To detect, whether the emissions affect our NEE flux estimates, the nighttime storage fluxes (Sect. 2.1.1) are plotted in wind rose form in Fig. 6. For enhanced visibility, only fluxes above 2 µmol $(m^2\,s)^{-1}$ are shown. The period with strong fire disturbances during the forest fires 2012 is excluded. We use the nighttime fluxes, because the emissions are preferably captured under stable atmospheric conditions, when the storage flux dominates the total flux and is most reliable. The result implies no significant effect, because the fluxes in the direction of the generators (marked by the light yellow arrow) are not particularly elevated.

Without an indication of a local pollution, we investigate our complete flux estimates in Fig. 7. The storage flux component is shown in grey. The available turbulent flux data has been added to the storage fluxes to provide the total NEE estimates in black. The error bars give the standard error of the mean of the monthly data.

Because there is no eddy covariance data for comparison in the first years, we make use of previous investigations from July 1996 (Schulze et al., 1999). To use this dataset as a reference is backed by other datasets in the boreal zone (Wang et al., 2007; Davis et al., 2003). The reference dataset has neither been corrected for storage fluxes nor it was turbulence filtered, which may cause a low bias during nighttime (Aubinet, 2008). Acevedo et al. (2004) also observed larger nocturnal fluxes (from the accumulation of CO_2 below the well-estimated boundary layer height) than expected from the eddy covariance technique. Indeed, the red line in Fig. 7 representing the reference eddy covariance dataset tends to lower flux estimates than our results. The general shape of the datasets compare well. Our average NEE estimate is $2.7 \pm 1.1\,\mu\text{mol}\,(\text{m}^2\,\text{s})^{-1}$ CO_2 for the nighttime from 23:00 to 04:00 in the years 2009–2011.

In the morning, the onset of photosynthesis is dominating the flux and is well captured. In July 2009, in the first half of the day, the photosynthetic uptake is well captured, peaking at about $-8\,\mu\text{mol}\,(\text{m}^2\,\text{s})^{-1}$. The other months show a slightly smaller carbon uptake, in line with earlier aircraft measurements over the site between −3.3 and $-9.6\,\mu\text{mol}\,(\text{m}^2\,\text{s})^{-1}$ (Lloyd et al., 2001).

The main shortcoming of our method becomes visible especially in the well-mixed afternoon hours, when the turbulent flux component dominates the total flux. We performed intensive data analysis to find indicators (e.g. the friction velocity and other turbulence parameters) how the data could be filtered, but did not succeed in finding a general method to validate the data points. Eventually, the presented diurnal averages give our best estimate of the carbon fluxes variations from 2009–2012.

A comparison between the different months reveal strong correlation of the CO_2 fluxes with the climatic conditions. In 2010, the ecosystem shows less activity than 2009, as the temperatures were lower. In 2011, the missing precipitation did not allow as much activity as in 2009. Finally, the forest fires, in combination with hot air temperatures and little rainfall, perturbed the ecosystem in 2012, such that a clear diurnal cycle could not even develop in July.

3.3 Comparison to eddy CO_2 fluxes

Since 20 June 2012, direct eddy covariance measurements are available for direct comparison to the flux assessments from the 300 m tall tower. Unfortunately, the data in summer 2012 was massivly influenced by the nearby forest fires. A snapshot from 24 July 2012 (Fig. 8a) reveals the difficulties of an in-situ comparison under these conditions, because the variing smoke plumes altered the measured concentrations arbitrarily, hence the flux estimates are widly fluctuating.

In the late summer, when the fire season came to an end and the atmosphere was less disturbed, the in-situ comparison between eddy covariance tower in the forest and the tall tower are much better (Fig. 8b). The onset of the atmospheric mixing in the morning hours can be seen earlier in the flux tower data, as the mixing starts at the ground and reaches the 30 m height much earlier than the 300 m level. In the afternoon, the eddy covariance method demonstrates its advantages: the turbulent flux component is still recorded in the late afternoon, when our 300 m storage flux is zero due to a well-mixed, homogenous boundary layer, and the turbulent correction term from the modified Bowen ratio method is not big enough to compensate.

Similar effects can be seen in the monthly averaged data in Fig. 7. The fire disturbed the signal in the summer months of 2012; therefore, this data is not accounted for the quantitative analysis. In the prior years, the eddy covariance data from 1996 gives a guidance how the data might look like. In June 2010 and July 2011, the capability of our method to correct turbulent fluxes is most evident. The storage flux levels off in the late afternoon, while the turbulent flux shifts the peak of the diurnal cycle towards the

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time, when the eddy covariance also showed highest activity. Another feature is visible in the months of August, when the strong peak of the storage component in the early morning is dampened by turbulent flux estimate towards the shape of the reference dataset.

In conclusion, our presented method can give a first estimate of the average CO_2 fluxes in the summer seasons. Its main weaknesses are the increased errors during the afternoon that do not allow the correct detection of the point in time of maximal photosynthetic uptake. Thus, our method provides a useful tool to estimate ecosystem activity, when eddy covariance measurements are not available. In turn, its particular strength is the nocturnal dataset.

3.4 CH_4 fluxes

In full analogy to our CO_2 flux analysis, the CH_4 total flux can be estimated as the sum of storage flux below 301 m level and the eddy flux at the highest level. Figure 9 shows the storage flux estimates in grey. Black dots sum eddy and storage fluxes and their error of the mean when summarizing each month.

The pattern is dominated by the storage flux. The mean of the total night-time flux (23:00 to 04:00) in all summer months 2009–2011 is $5.6 \pm 4.5\,\mathrm{nmol\,(m^2\,s)^{-1}}$. To compare this number we convert different units in other publications to $\mathrm{nmol\,(m^2\,s)^{-1}}$ ($10\,\mathrm{nmol\,(m^2\,s)^{-1}} = 0.86\,\mathrm{nmol\,(m^2\,day)^{-1}} = 0.054\,\mathrm{mg\,(m^2\,day)^{-1}}$ CH_4). Typical magnitudes of CH_4 fluxes vary widely and depend on measurement type, temperature, water level and topography. Aircraft measurement in Siberia give 3 to $106\,\mathrm{nmol\,(m^2\,s)^{-1}}$ (Glagolev et al., 2008). Chamber measurements in Canada result in fluxes at the edge of a fen of $12.5\,\mathrm{nmol\,(m^2\,s)^{-1}}$ (Rask et al., 2002). Modified Bowen ratio method at a tall tower in boreal US give summer fluxes of $17.4 \pm 10.4\,\mathrm{nmol\,(m^2\,s)^{-1}}$ (Werner et al., 2003). Finally, eddy measurements show typical summer emissions of $2.5\,\mathrm{nmol\,(m^2\,s)^{-1}}$ in a Finnish boreal fen (Rinne et al., 2007). Our data represents a case in point.

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The most remarkable feature occurs during the morning transition, when estimated CH_4 fluxes show values up to 130 nmol $(m^2 s)^{-1}$ (∼ 180 mg $(m^2 d)^{-1}$). The most probable reason for this is the topography around the tower. The tower is located on a hill and is surrounded by bogs. During night, the lower air layers cool down and the evolving temperature inversion captures the emitted CH_4; it is accumulated close to the ground in the topographic depression, causing flux signals not to reach the tower. That is why our data is close to zero around midnight. With sunrise, the air layers mix up to higher altitudes and pass by along the 301 m tower. While rising from below to the height of the tower, a large positive flux signal occurs, whereas the venting aloft the control volume compensates the flux balance with negative fluxes thereafter (Fig. 10). Thus, the morning signal mimics the real flux from a different time and place.

Mesoscale models were able to reproduce that the local topography drives a nocturnal buildup in the Yenisei river basin about 30 km east of the station in case of CO_2 (van der Molen and Dolman, 2007). Because CH_4 fluxes show heterogeneities on even smaller scale – depending on landscape patterns such as forests, and bogs (Flessa et al., 2008) – our explanation seems realistic.

To localize the origin of the air, the (continuously available) storage flux term is plotted in a wind rose in Fig. 11. For better visibility, only distinct signals with fluxes more than 30 nmol $(m^2 s)^{-1}$ are shown. The most frequent direction coincides with the direction of the power generator. Since the fluxes are not particularly elevated, and the maximum flux appears in the morning (whereas the generator runs continuously), we assume the generator not to be the influential emission source. In fact, some more strong signals arrive from northeastern and eastern direction, where the closest bog to the station is located (yellow hatched area). In southeastern direction, another large mire is located, which probably gives the reason for the dominant peak in the wind rose. These findings underline our reasoning of the topographic influence on the ZOTTO flux signal.

In essence, the average nocturnal flux may mainly characterize the surrounding forests with small contributions of surrounding bogs, depending on the wind direction (footprint see Fig. 2). However, if we assume that the total positive CH_4 flux signal in the morning hours (06:30–09:00 h) is a very local effect and represents the integral flux of the nearby bog during the whole night (23:00–06:30 h), we obtain CH_4 fluxes up to 27.4 nmol $(m^2\,s)^{-1}$ in July 2009. The future CH_4 flux measurements (starting after repair in the 2013 vegetation season) will improve further investigation on this topic.

4 Summary and conclusion

We estimate ecosystem fluxes from concentration gradients from six height levels (301 m, 228 m, 158 m, 92 m, 52 m, 4 m) at the ZOTTO station for the period since 2009, when neither aircraft nor eddy covariance data were available. We gain most reliable information during night, when the gases are captured in the nocturnal boundary layer and distinct differences between the measurement levels develop; the storage term is dominating the total flux (i.e. 95 % for CO_2 flux). Additionally, we used measured sensible heat fluxes to correct for the turbulent flux components using the modified Bowen ratio method.

The CO_2 fluxes reveal a reasonable diurnal shape and magnitude compared to previous data and the newly installed eddy covariance towers. The night-time fluxes (23:00 to 04:00) are 2.7 ± 1.1 µmol $(m^2\,s)^{-1}$ CO_2 in the summer months June–September 2009–2011. The full diurnal cycle is still covered by uncertainties through the modified Bowen ratio method, especially during well-mixed periods with potential temperature gradients close to zero.

The CH_4 fluxes are predominantly characterized by the morning transition, when emitted CH_4 from the surrounding bogs vents by the tower due to the beginning mixing of air by sun. The night-time fluxes (23:00 to 04:00) are 5.6 ± 4.5 nmol $(m^2\,s)^{-1}$ CH_4 in the summer months, and are feasible when comparing to the wide range given by other investigations. The wind directions with the largest flux contributions indicate the nearby bogs as the main emission source (up to 27.4 nmol $(m^2\,s)^{-1}$ average flux in July 2009).

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In conclusion, our method is a good basis to estimate carbon budgets for stations that have no direct eddy covariance data available. The method is also applicable to other gas species and also in winter periods, but the wind measurements needs improvement before. In future, data series through the year may enable further improvements for the process understanding of the fluxes, e.g. observed differences in transport between the seasons and different air flow conditions (Eneroth et al., 2003).

Acknowledgements. The ZOTTO project is funded by the Max Planck Society through an International Science and Technology Center (ISTC) partner project no. 2757 within the framework of the proposal "Observing and Understanding Biogeochemical Responses to Rapid Climate Changes in Eurasia".

We thank E.-D. Schulze for the reference data. We thank the technical staff from the Max Planck Institute for Biogeochemistry in Jena for maintaining the ZOTTO station and setting up the eddy covariance towers, especially K. Kübler, S. Schmidt, J. Lavric, and M. Hertel. Special thanks for the panorama photo go to M. Hielscher. For servicing the setup at the ZOTTO site, we thank for the work of A. Panov, A. Zukanov, N. Sidenko, A. Timokhina, and S. Titov from the Sukachev Institute of Forest in Krasnoyarsk, Russia. We thank J. Mayer to share his ideas, how to improve the manuscript.

The service charges for this open access publication
have been covered by the Max Planck Society.

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Table 1. Yearly averaged climatic conditions at ZOTTO during the summer months June–September.

Summer in the year	2009	2010	2011	2012
Air temperature $T_{4\,m}$ [°C]	14.7	12.5	14.5	16.6
Temperature range T_{min}–T_{max} [°C]	−1.3–33.2	−2.6–31.4	−0.1–32.4	2.3–36.7
Rain [mm]	123.5	122.9	74.1	49.2
Photosynthetically active radiation [µmol $(m^2 s)^{-1}$]	342.0	295.3	320.3	307.2

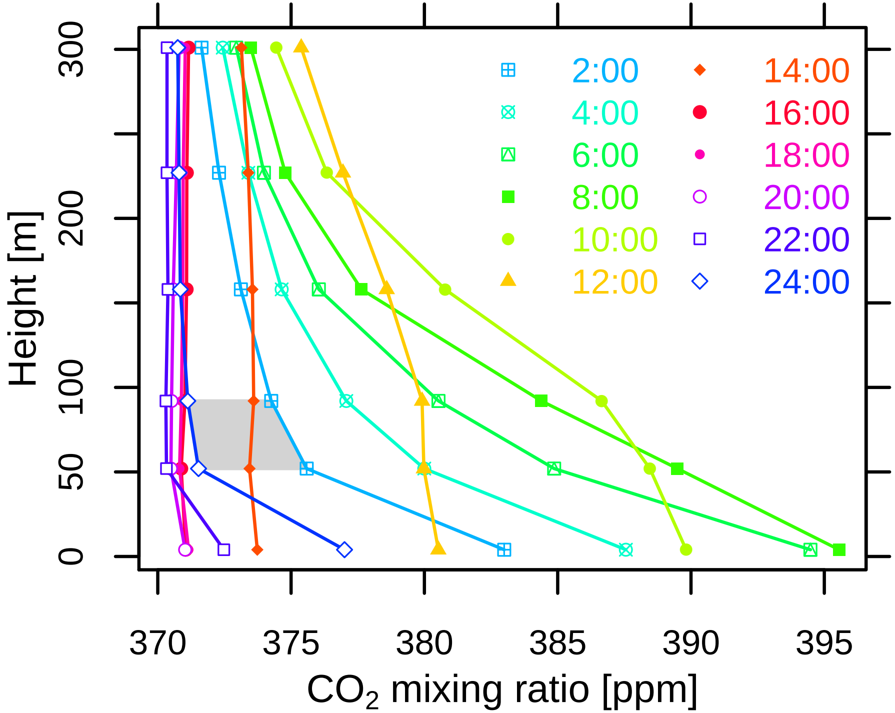

Fig. 1. Average diurnal development of the CO_2 profile along the tall tower during July 2009; grey shaded area illustrates storage flux component between 52 m and 92 m level and between 00:00 and 02:00 KRAT.

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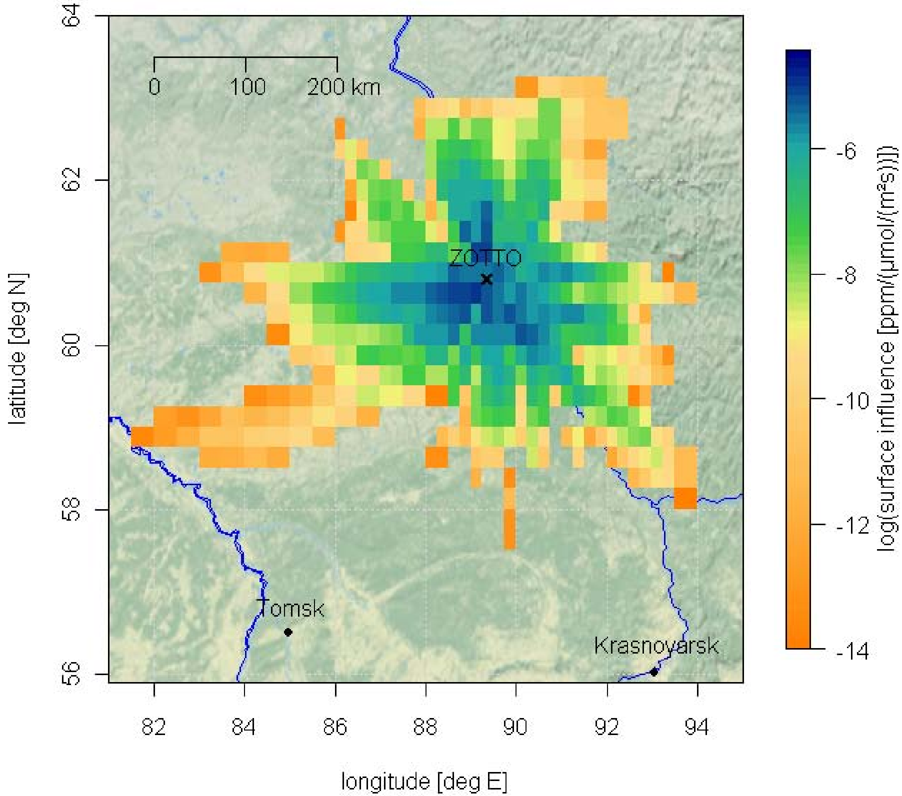

Fig. 2. Nocturnal footprint of ZOTTO station at 301 m level for months June to September 2009 (based on back trajectories from 5.00 a.m. back to 11.00 p.m. the previous evening with the STILT model).

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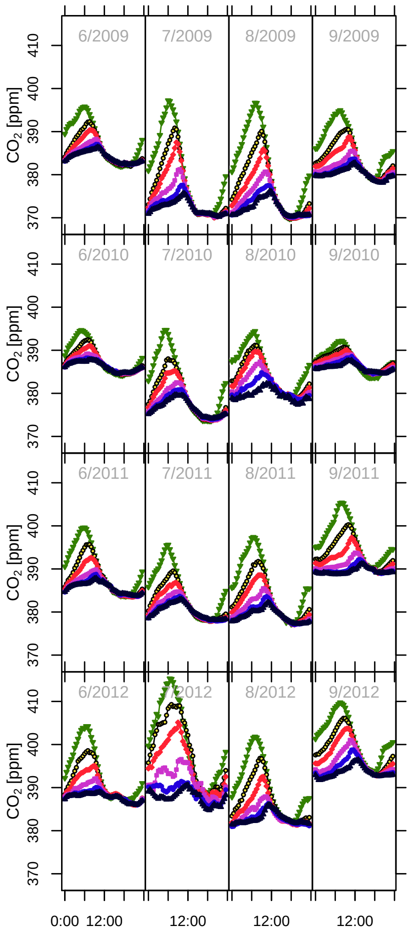

Fig. 3. CO_2 diurnal cycle, averaged for individual months and years.

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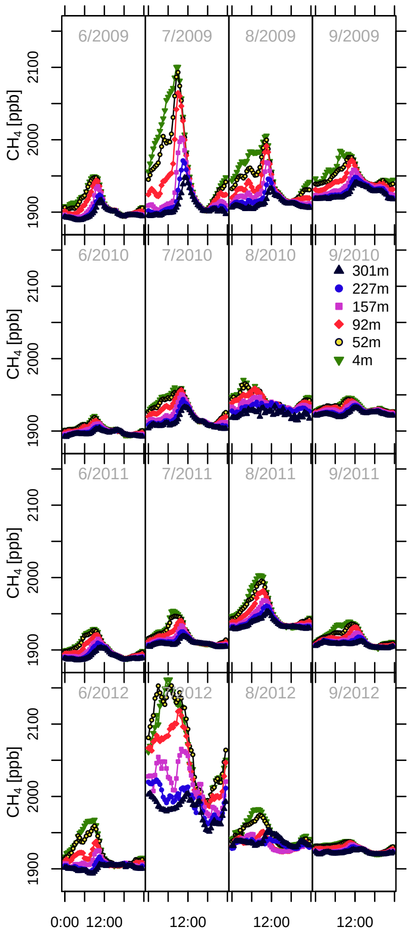

Fig. 4. CH_4 diurnal cycle, averaged for individual months and years.

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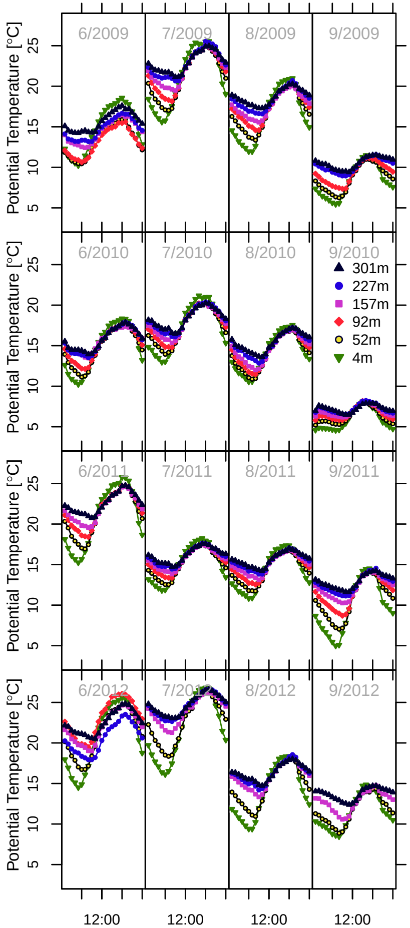

Fig. 5. Diurnal cycle of potential Temperature for individual months.

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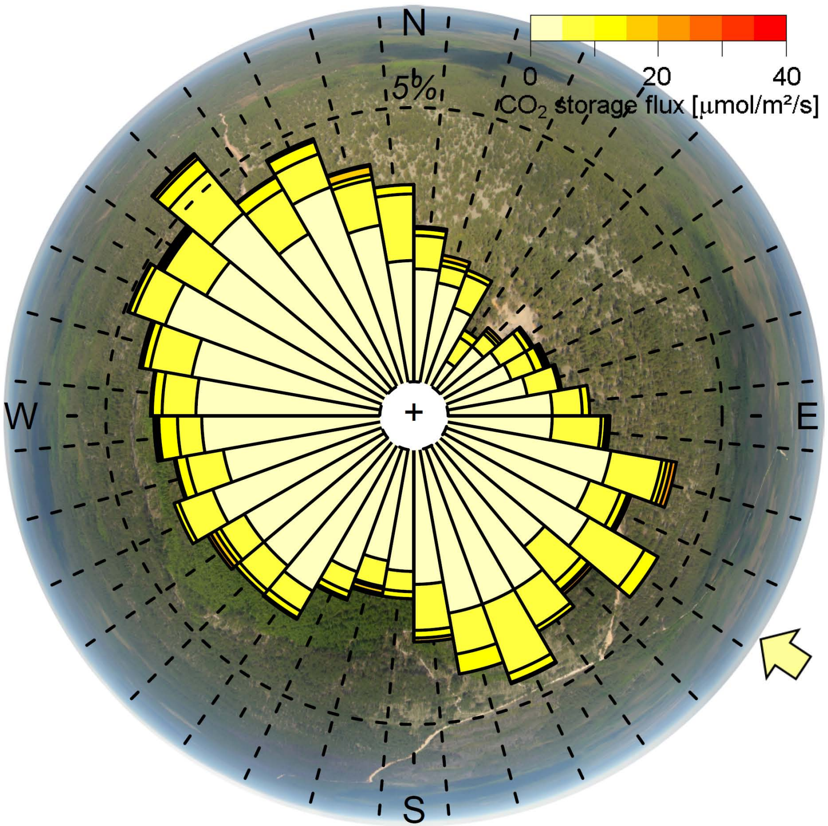

Fig. 6. Top view of ZOTTO centered on the tower with overlaid night time storage flux estimates (23:00 to 06:00; $> 2\,\mu\text{mol}\,(\text{m}^2\,\text{s})^{-1}$ only) vs. wind direction for all summer months June–September 2009–2011; length of the pedals give the frequency how often flux from this direction was measured; colors indicate the strength of the storage flux; the arrow indicates the direction of the power generator.

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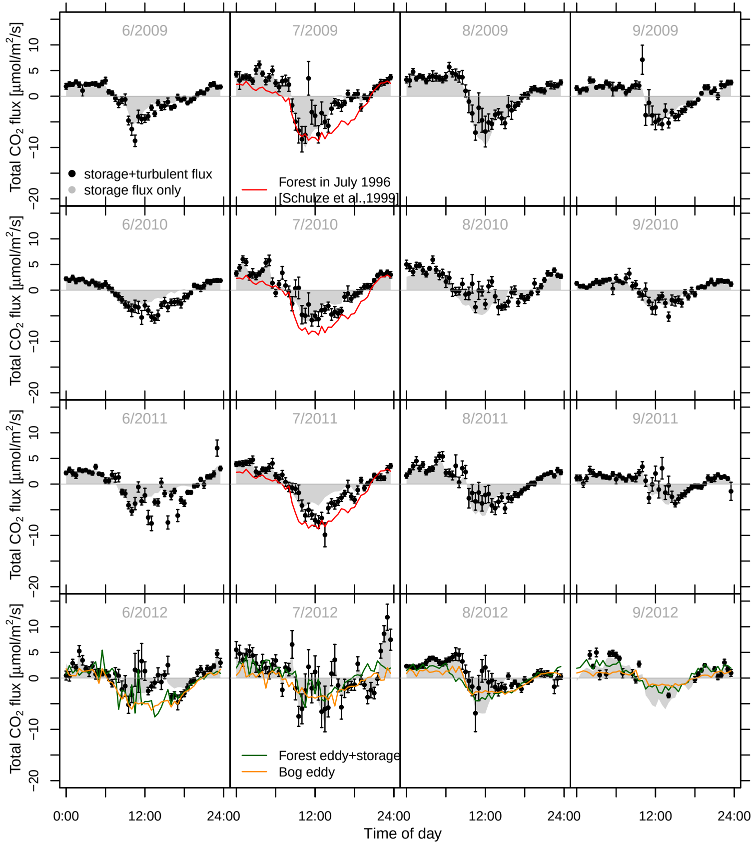

Fig. 7. Diurnal cycle of the total CO_2 flux estimate with standard error of the mean for all summer months; grey area indicates the storage flux component; for guidance: red line: eddy covariance data in July 1996 from 67 yr old stand in Zotino from (Schulze et al., 1999); green line: eddy covariance data and storage flux from the new forest site; orange line: eddy covariance data from the new bog site

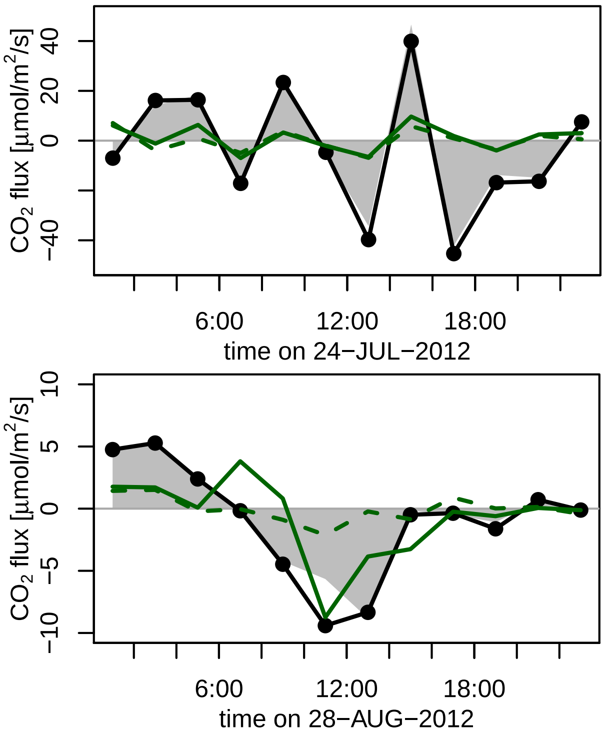

Fig. 8. Exemplarily in-situ comparison between the measurements at the tall tower (grey area represents the storage flux, black line is storage + turbulent flux) and the forest flux tower (storage flux as dark green dashed line, Eddy covariance + storage flux as dark green line); top: during strong forest fires near the site on 24 July 2012; bottom: during late summer on 28 August, 2012.

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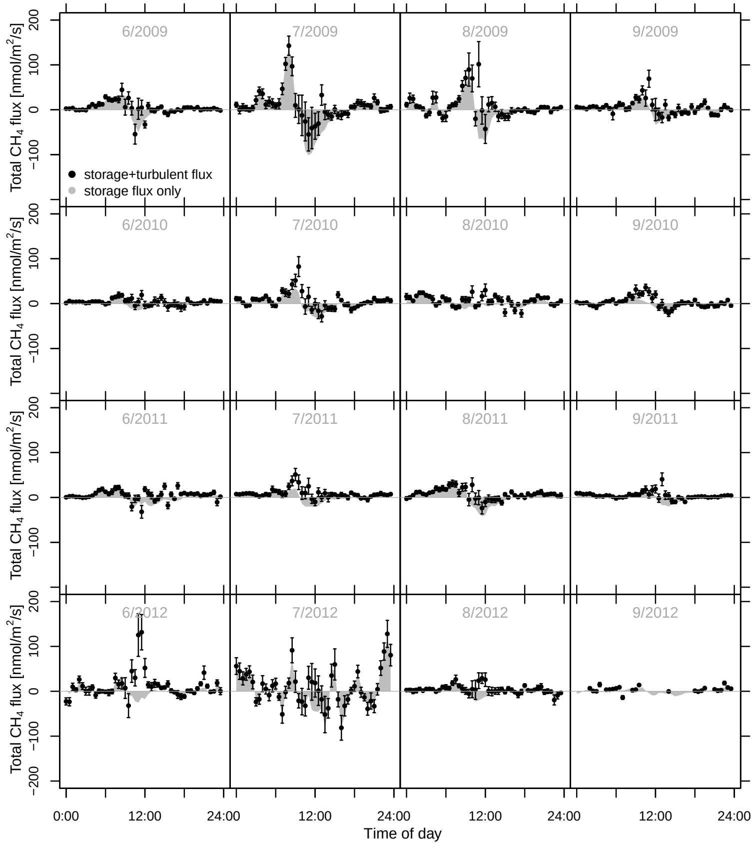

Fig. 9. Diurnal cycle of total CH_4 flux estimate with standard deviation of the mean for all summer months in black; grey area indicates storage flux component.

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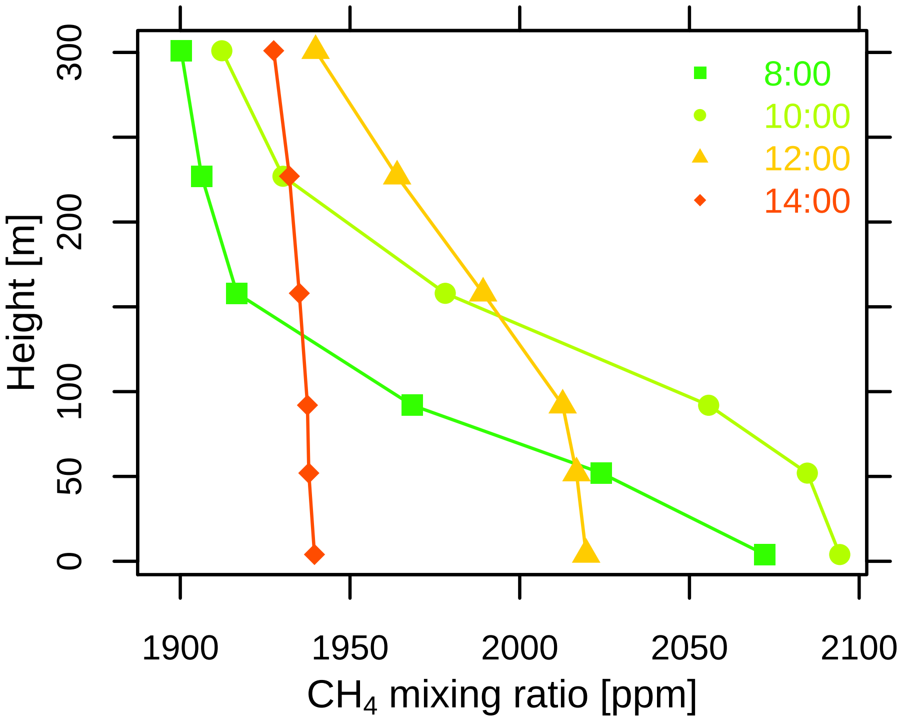

Fig. 10. Diurnal variation of the CH_4 mixing ratio at ZOTTO tower in July 2009.

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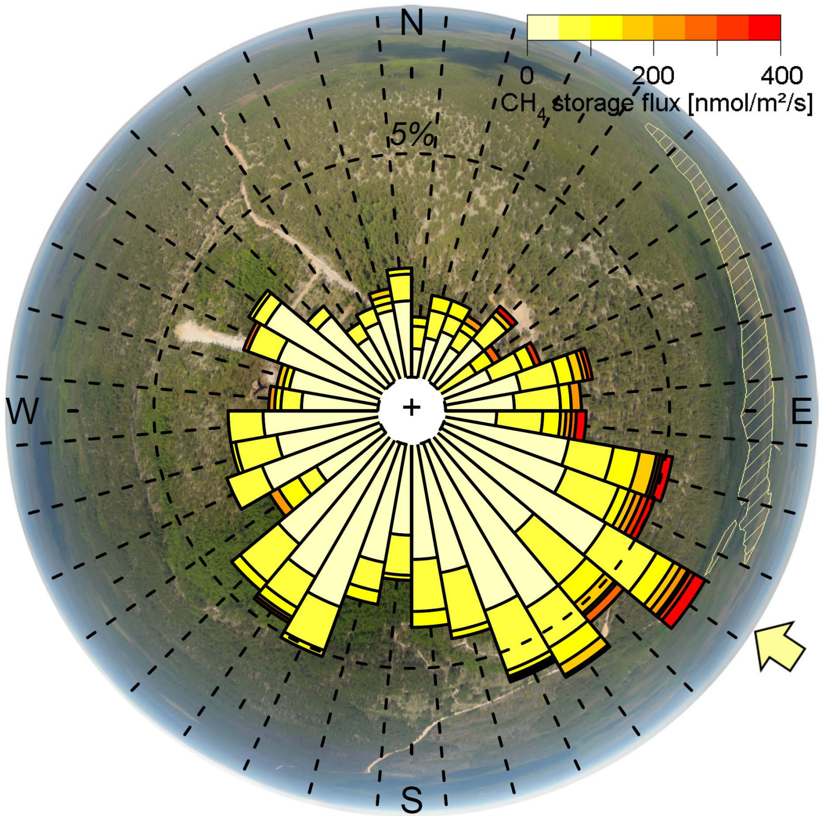

Fig. 11. Top view of ZOTTO centered on the tower with overlaid night time storage flux estimates (23:00 to 08:00 KRAT; > 30 nmol $(m^2\ s)^{-1}$ only) vs. wind direction for all summer months June-September 2009-2011; overall length of the pedals give frequency how often flux from this direction is measured; the arrow indicates the direction of the power generator, the hatched area marks the closest bog.

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