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Inferences from CO_2 and CH_4 concentration profiles at the Zotino Tall Tower Observatory (ZOTTO) on regional summertime ecosystem fluxes

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Abstract. The Siberian region is still sparsely covered by ecosystem observatories, which motivates the exploitation of existing data sets to gain spatially and temporally better-resolved carbon budgets. 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 beginning 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 regional fluxes, especially during nighttime. 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 obtained average nighttime fluxes (23:00 to 04:00 local time) are $2.7 \pm 1.1\,\mu\text{mol}\,(\text{m}^2\,\text{s})^{-1}$ for CO_2 and $5.6 \pm 4.5\,\text{nmol}\,(\text{m}^2\,\text{s})^{-1}$ for CH_4 during the summer months June–September in 2009 and 2011. During the day, the method is limited due to numeric instabilities because of vanishing vertical gradients; however, the derived CO_2 fluxes exhibit reasonable diurnal shapes and magnitudes compared to the eddy covariance technique, which became available at the site in 2012. Therefore, the tall tower data facilitate the extension of the new eddy covariance flux data set backward 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 pollution 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 measurement devices 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 the 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 for first flux estimates with transport inversion models on the regional scale (Winderlich, 2012; Saeki et al., 2013).

1.2 Regional flux estimation techniques

The observation of the atmospheric gas composition is one method among several others to gain information about surface carbon fluxes. The eddy covariance technique allows for direct carbon flux measurements through 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 such 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 1990s. But most of them are not in service any more; for example, 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 only recently (Rinne et al., 2007). In Siberia, the predominant way to determine CH_4 fluxes has been by chamber measurements.

The rather small area of less than 1 km^2 covered 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 planetary boundary layer and the overlaying free troposphere are used to estimate ecosystem fluxes on regional scales 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) . Here, 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

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

At the ZOTTO site, greenhouse gas concentrations have been recorded since 2007 (Kozlova et al., 2008). In 2009, a new system based on the cavity ring-down spectroscopy was installed to measure CO_2, CH_4, and H_2O and meteorological data at six height levels: 4, 52, 92, 158, 227 and 301 m a.g.l. (Winderlich et al., 2010). Each of the six tower inlets is continuously flushed through 8L 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 six tower levels are equipped with 3-D sonic anemometers for 3-D wind measurement, with temperature, humidity and pressure (see Supplement in Winderlich et al., 2010).

In June 2012, two eddy covariance towers started operation near the ZOTTO site. One is located 900 m to the north-northeast in the pine forest; the other is located 3 km to the northeast in a bog. Both towers are equipped with an enclosed CO_2 / H_2O gas analyzer (LI-7200, LI-COR Inc., USA), a 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 was 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 data sets for spatially and temporally better resolved fluxes. Therefore, we explore in this paper how much information on regional carbon fluxes can be extracted from the CO_2 and CH_4 concentration profile along the 301 m tall ZOTTO station starting in 2009. We will make use of the heat flux measurements to analyze our data set. This may eventually allow us to extend the newly installed eddy covariance flux data set backward in time. In turn, this eddy covariance data set is also used to evaluate the quality of our surface flux 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):

$$\mathrm{NEE} = F_{\mathrm{Stor}} + F_{\mathrm{Eddy}} + F_{\mathrm{adv}} = \int_0^{z_\mathrm{r}} \frac{1}{V_\mathrm{m}} \cdot \frac{\partial \bar{c}}{\partial t} \mathrm{d}z + \frac{1}{V_\mathrm{m}} \cdot \overline{w'c'}(z_\mathrm{r}) + \ldots, \quad (1)$$

where w is the wind component in the 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 $V_\mathrm{m}(z) = M_{\mathrm{Air}}/\rho_{\mathrm{Air}}(z)$ is the molar volume. The sign convention used here gives positive NEE for ecosystem emissions, where a positive flux term (i.e., source) corresponds to 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., 2004, 2008; Aubinet et al., 2005, 2010; Aubinet, 2008; 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 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 (see Chapter D3.3 in Winderlich, 2012, and Figs. S5 and S6 in the Supplement). Note that they have been disregarded in other studies as well (Haszpra et al., 2005).

All calculations are based on 30 min time steps. All CO_2 and CH_4 measurements (recorded every 18 min for every height) are averaged within a specific 30 min interval, which is determined by the time stamp of the meteorological data set (temperature, heat flux, etc.). The time is given for the Krasnoyarsk time zone (KRAT = UTC + 7 h), which is shifted by 1 h compared to local solar time (LOC = KRAT − 1 h). Please note that the 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 become negligible (Davis et al., 2003).

2.1.1 Storage flux

The storage term F_{Stor} in Eq. (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 nighttime, 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. Over the course of the day, the planetary boundary layer is relatively well mixed, and photosynthesis therefore reduces the CO_2 concentration at all heights.

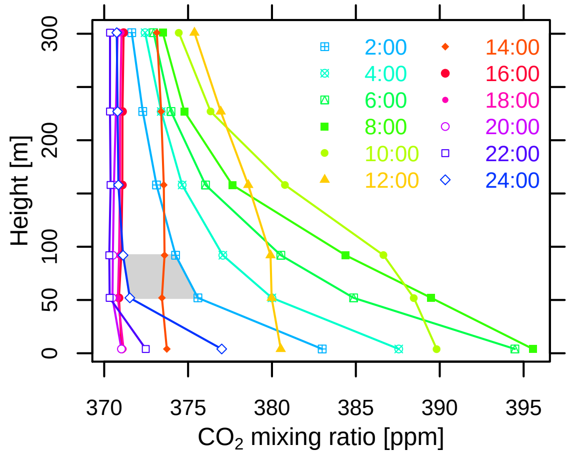

Fig. 1. Average diurnal development of the CO_2 profile along the tall tower during July 2009; the grey-shaded area illustrates storage flux component between 52 and 92 m and between 00:00 and 02:00 KRAT.

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

$$F_{\mathrm{Stor}}(t_i, z_h) = \int_{z_{h+1}}^{z_h} \frac{1}{V_\mathrm{m}} \cdot \frac{\partial \bar{c}(t_i)}{\partial t} \mathrm{d}z = \int_{z_{h+1}}^{z_h} \frac{\rho_{\mathrm{Air}}(z)}{M_{\mathrm{Air}}} \cdot \frac{\partial \bar{c}(t_i)}{\partial t} \mathrm{d}z$$
$$\cong \sum_{h=1}^{5} \frac{\frac{1}{2}(\rho_h + \rho_{h+1})}{28.9644\,\mathrm{g\,mol^{-1}}} \cdot \frac{\frac{1}{2}\left((c_h(t_{i+1}) - c_h(t_i)) + (c_{h+1}(t_{i+1}) - c_{h+1}(t_i))\right)}{t_{i+1} - t_i} \cdot (z_h - z_{h+1}), \quad (2)$$

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, 227 m, 158 m, 92 m, 52 m, 4 m) and 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 the 4 m level is assumed constant.

The storage flux F_{Stor} reaches its maximum during nighttime from 23:00 to 04:00, 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 converse approach to the eddy covariance technique, which primarily measures the turbulent flux and requires the storage flux as an important correction term especially during nighttime and under low turbulence conditions (see Fig. 5.2 in Aubinet et al., 2012). Thus, the flux estimates derived by our method tend 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 ($\sim$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 $\sim$40 min. $\sim$0.0004 Hz) our data do not allow for direct eddy flux measurements F_{Eddy} at the tall tower.

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

$$F_{\text{Eddy}} \cdot V_{\text{m}} = \overline{w'c'} = K_C \frac{\mathrm{d}c}{\mathrm{d}z}. \tag{3}$$

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 $\mathrm{d}T_{\text{pot}} / \mathrm{d}z$:

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

Similarity for gas and heat implies $K_{\text{C}} = K_{\text{T}}$. The combination of Eqs. (3) and (4) and following the "modified Bowen ratio method" (Businger, 1986) obtains

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

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

Our approach has certain limitations. Models show dissimilarities between heat and CO_2 fluxes (Huang et al., 2009). 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 were found to be the same within about 10–12 % (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, for example, 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, ΔTemp = 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 $(m^2\,s)^{-1}$ and 5000 nmol $(m^2\,s)^{-1}$ for CO_2 and CH_4, respectively ($< 2\,\%$ of all data).

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. With the onset of mixing in the morning hours, the flux signal from the ground reaches higher tower levels (see Figs. S2 and S3 in the Supplement). The 301 m height of the ZOTTO tower is sufficient to capture most of the NEE as storage flux already, at least during nighttime, 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, which 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 have been 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 eddy covariance tower in the bog measures the turbulent fluxes at 9 m height. The tower in the forest stand is equipped with eddy covariance instruments at 30 m height, and additionally detects the CO_2 profile at nine height levels (0.1, 0.3, 1.0, 2.0, 5.0, 9.0, 15.0, 22.0 and 30.0 m) to correct for the storage flux component.

2.3 Footprint

To correctly attribute the measurement signals 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 3-hourly

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

Year of the summer	2009	2010	2011	2012
Air temperature $T_{4\,\mathrm{m}}$ (°C)	14.7	12.5	14.5	16.6
Temperature range $T_{\min}$ to $T_{\max}$ (°C)	−1.3 to 33.2	−2.6 to 31.4	−0.1 to 32.4	2.3 to 36.7
Rain sum (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

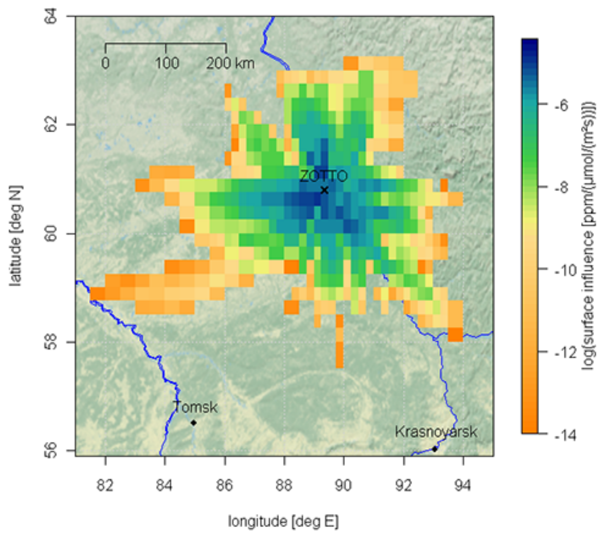

Fig. 2. Nocturnal footprint of ZOTTO station at the 301 m level for months June to September 2009 (based on back trajectories from 05:00 back to 23:00 the previous evening with the STILT model).

short-term forecast fields from the operational archive of the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/), to get an overview of the origin of air parcels arriving at ZOTTO.

As the storage flux drives our total flux estimates predominantly during nighttime, 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 23:00 to 05:00 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 regional storage flux signal covers 35 000 km^2, 99 % of the signal arrives from within 250 km, and half of the cumulated surface influence signal originates from a distance less than 90 km. The size of the nighttime footprint of the tower will decrease for lower tower levels. Since the land cover in the footprint area is relatively homogenous and without major anthropogenic distortions, the regional flux estimates will represent an average of the western Siberian boreal region including its characteristic mixture of forests and bogs.

The footprint of a concentration measurement differs from this of a direct turbulent flux measurement (Schmid, 1994; Sect. 8.2.4 in Rannik 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 1.7 km for the forest, and 1.3 km for the bog. Therefore, the two towers represent their surrounding local ecosystems well, while the footprint of the tall tower averages all flux contributions from a much larger area, and cannot be attributed to a specific ecosystem.

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 nighttime, the emitted gases are trapped in the nocturnal boundary layer close to the ground. The lowest level, 4 m, experiences the strongest concentration increase, but even the 301 m level is partially influenced by nocturnal boundary layer air. During daytime, the atmospheric boundary layer becomes well mixed and the gas concentrations become nearly indistinguishable at the different height levels (compare discussion to Fig. 1).

The diurnal behavior of the CO_2 and CH_4 profiles is 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 of a very stable layering of the nocturnal boundary layer, a temperature inversion. During daytime, potential temperatures at all heights adjust to a common temperature; the boundary layer is well mixed. Additional illustrations of the diurnal evolution of the measured parameters along the tall tower profile are shown in the Supplement (e.g., Fig. S1).

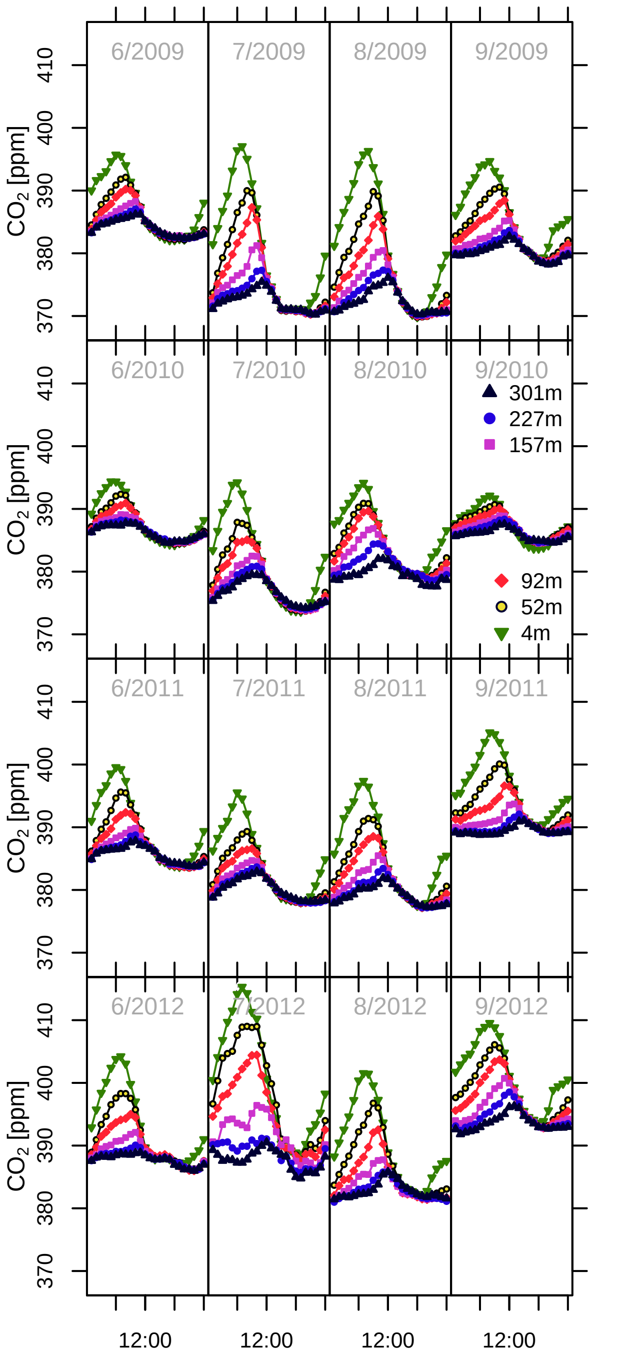

Fig. 3. CO_2 diurnal cycle, averaged for individual months and years.

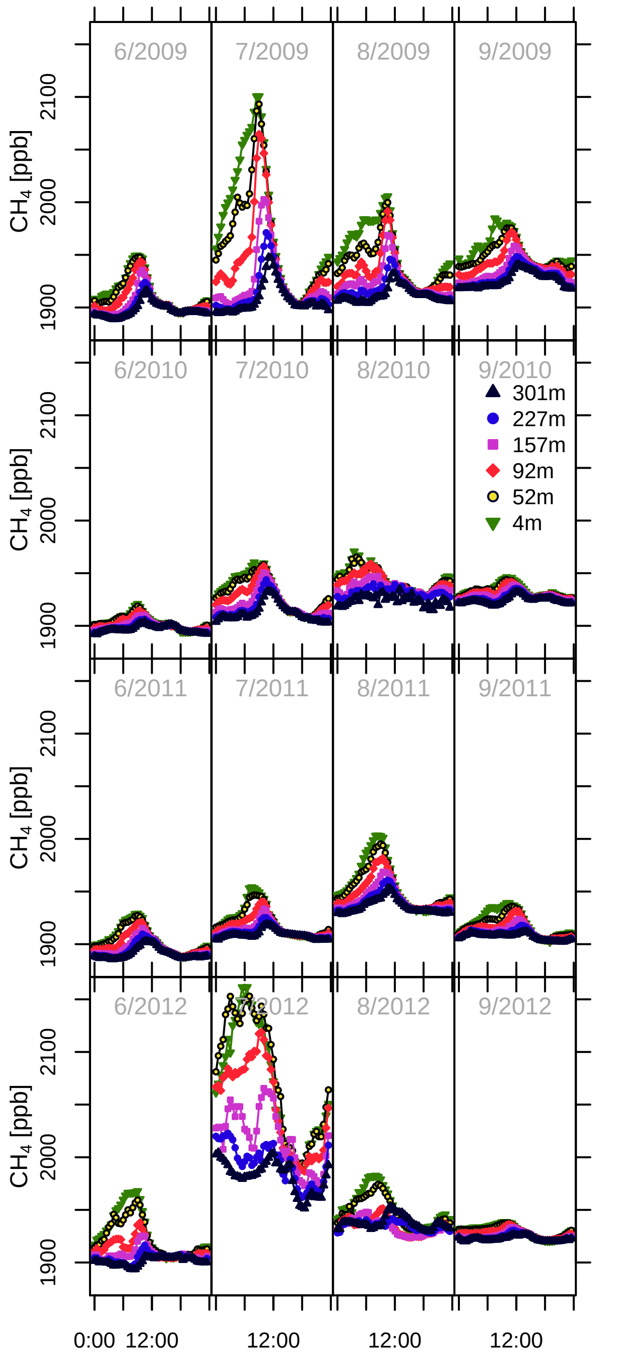

Fig. 4. CH_4 diurnal cycle, averaged for individual months and years.

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, for example 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 compared to the other years (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

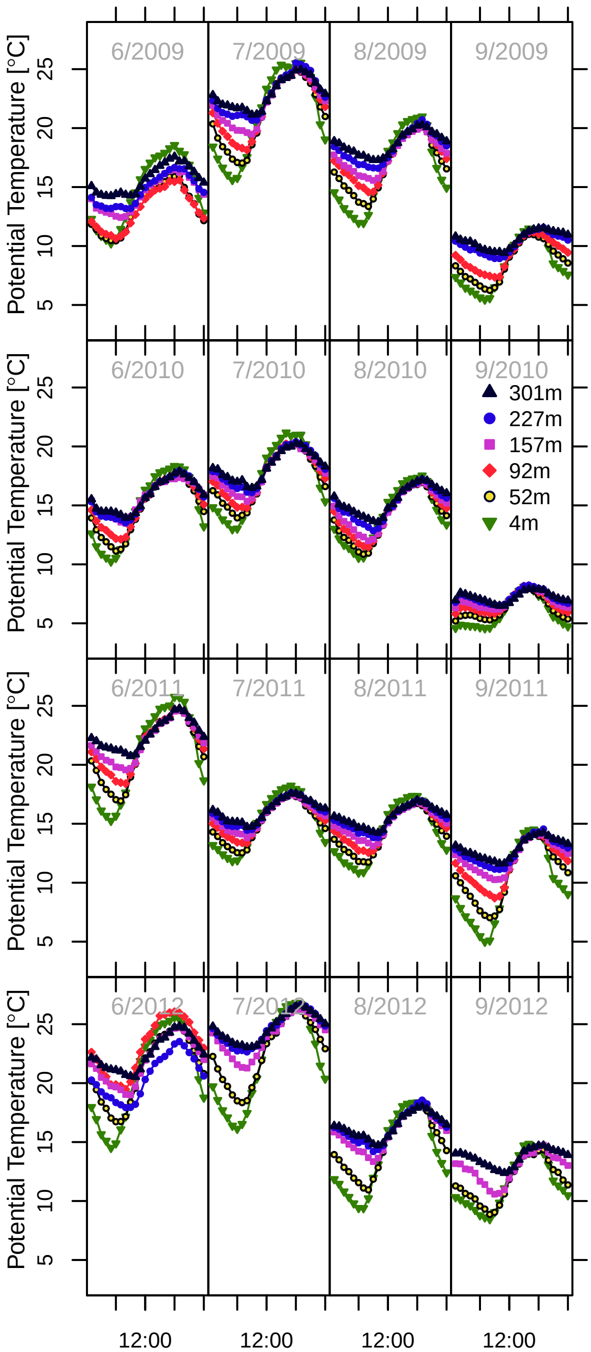

Fig. 5. Diurnal cycle of potential temperature, averaged for individual months and years.

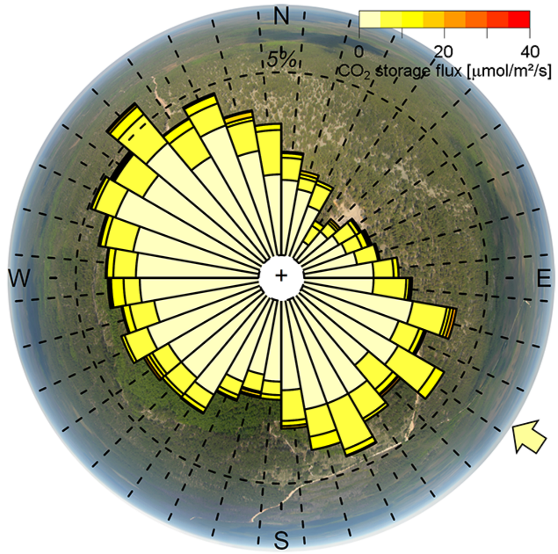

Fig. 6. Top view of ZOTTO centered on the tower with overlaid nighttime storage flux estimates (23:00 to 06:00, > 2 µmol $(m^2\ s)^{-1}$ only) vs. wind direction for all summer months June–September 2009–2011: the lengths of the petals show how often a flux from this direction was measured, colors indicate the strength of the storage flux and the arrow indicates the direction of the power generator.

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 in 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 have 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 are no eddy covariance data for comparison in the first years, we make use of previous investigations from July 1996 (Schulze et al., 1999). The use of this data set as a reference is backed by other data sets in the boreal zone (Wang et al., 2007; Davis et al., 2003), since they also show the same diurnal patterns; however, the amplitudes vary

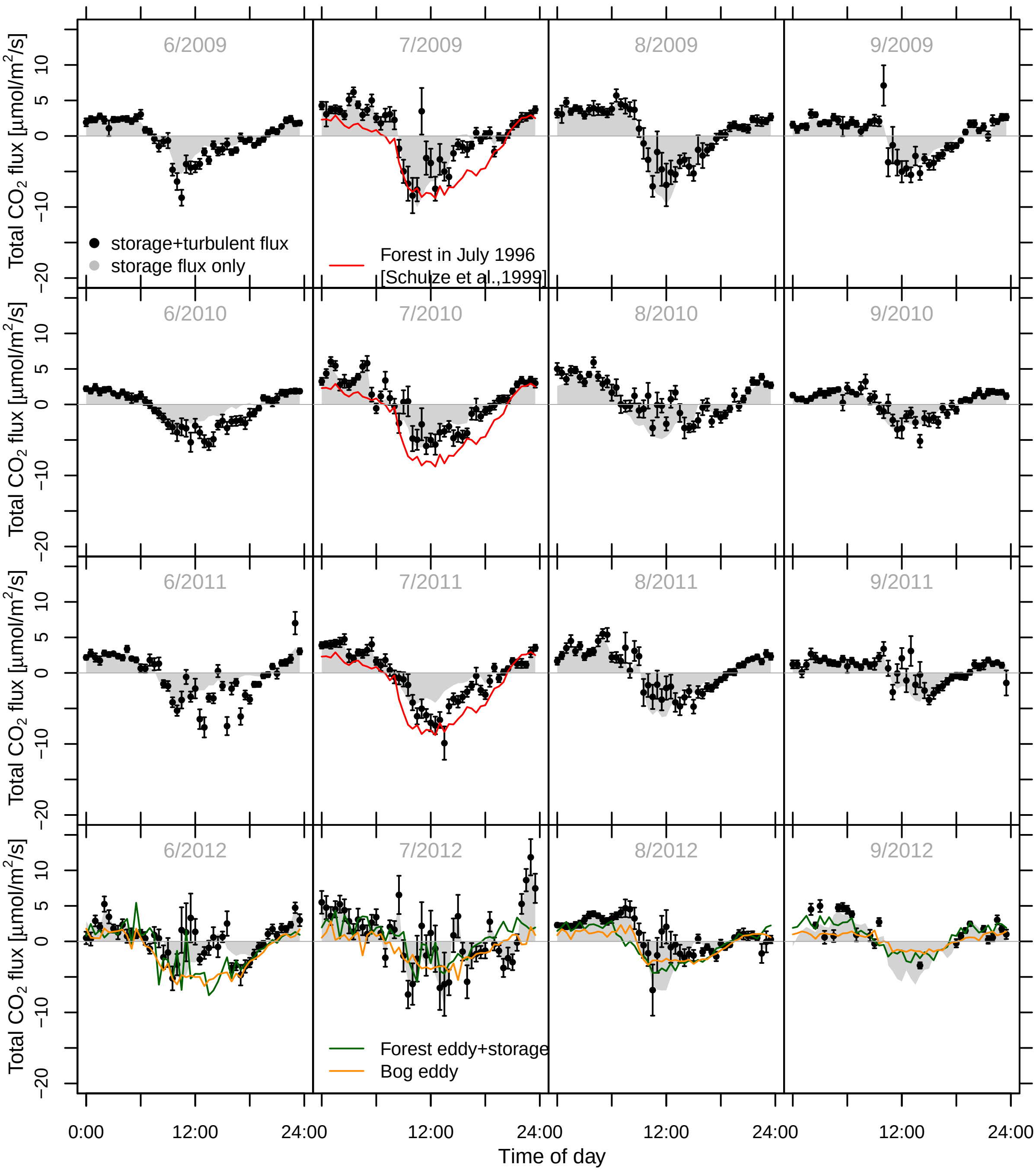

Fig. 7. Diurnal cycle of the total CO_2 flux estimate with standard error of the mean for all summer months: the grey area indicates the storage flux component; (for guidance) red line: eddy covariance data in July 1996 from a 67-year-old stand in Zotino from Schulze et al. (1999); green line: eddy covariance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

with meteorological conditions. The reference data set has not been corrected for storage fluxes, nor was it 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 data set tends toward lower flux estimates than our results. The general shapes of the data sets compare well. Our average NEE estimate is

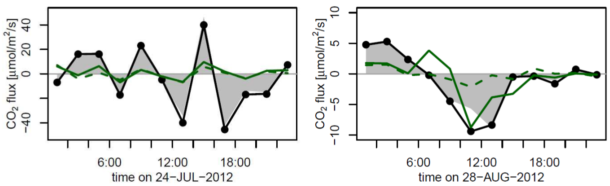

Fig. 8. Example in situ comparison between the measurements at the tall tower (the grey area represents the storage flux and the black line is storage + turbulent flux) and the forest flux tower (storage flux as the dark green dashed line, eddy covariance + storage flux as the dark green line): left: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

$2.7 \pm 1.1\,\mu mol\,(m^2\,s)^{-1}$ 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 $-8\,\mu mol\,(m^2\,s)^{-1}$. The other months show a slightly smaller carbon uptake, in line with earlier aircraft measurements over the site between -3.3 and $-9.6\,\mu mol\,(m^2\,s)^{-1}$ (Lloyd et al., 2001).

The main shortcoming of our method becomes especially visible in the well-mixed afternoon hours, when the turbulent flux component dominates the total flux. While the amplitude of the flux may alter with the meteorological conditions, the different shape between our data set and the reference suggests a missing flux component during the most turbulent part of the day. Given the homogenous countryside, there is no evidence why the diurnal flux cycle should have changed its pattern. We performed intensive data analysis to find indicators (e.g., the friction velocity and other turbulence parameters) of how the data could be filtered, but did not succeed in finding a general method to validate the data points. Recent studies indicate that our way of a temporally averaged storage flux measurement may inherently miss high-frequency flux structures, especially under turbulent conditions (Finnigan, 2006). Eventually, the presented diurnal averages give our best estimate of the carbon fluxes variations from 2009 to 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 have been available for direct comparison to the flux assessments from the 301 m tall tower. Unfortunately, the data in summer 2012 were massively influenced by nearby forest fires. A snapshot from 24 July 2012 (Fig. 8, left) reveals the difficulties of an in situ comparison under these conditions, because the varying smoke plumes altered the measured concentrations arbitrarily, hence the flux estimates are widely fluctuating.

In the late summer, when the fire season came to an end and the atmosphere was less disturbed, the in situ comparison between the eddy covariance tower in the forest and the tall tower is much better (Fig. 8, right). 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 301 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 301 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, these data are not accounted for in the quantitative analysis. In the prior years, the eddy covariance data from 1996 give guidance how the data might look like. The capability of our method to correct turbulent fluxes is most evident in June 2010 and July 2011. The storage flux levels off in the late afternoon, while the turbulent flux shifts the peak of the diurnal cycle towards the time when the eddy covariance also showed highest activity. Another feature is visible in each 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 data set.

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 for the correct detection of the point in time of maximal photosynthetic uptake. Thus, our method provides a useful tool for estimating ecosystem activity when eddy covariance measurements are not available. Its particular strength is the nocturnal data set.

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 the 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 nighttime flux (23:00 to 04:00) in all summer months of 2009–2011 is $5.6 \pm 4.5\,nmol\,(m^2\,s)^{-1}$. To compare this number we convert different units from other publications into $nmol\,(m^2\,s)^{-1}$ ($10\,nmol\,(m^2\,s)^{-1}$ = $0.86\,nmol\ (m^2\,day)^{-1} = 0.054\,mg\,(m^2\,day)^{-1}$ CH_4). Typical

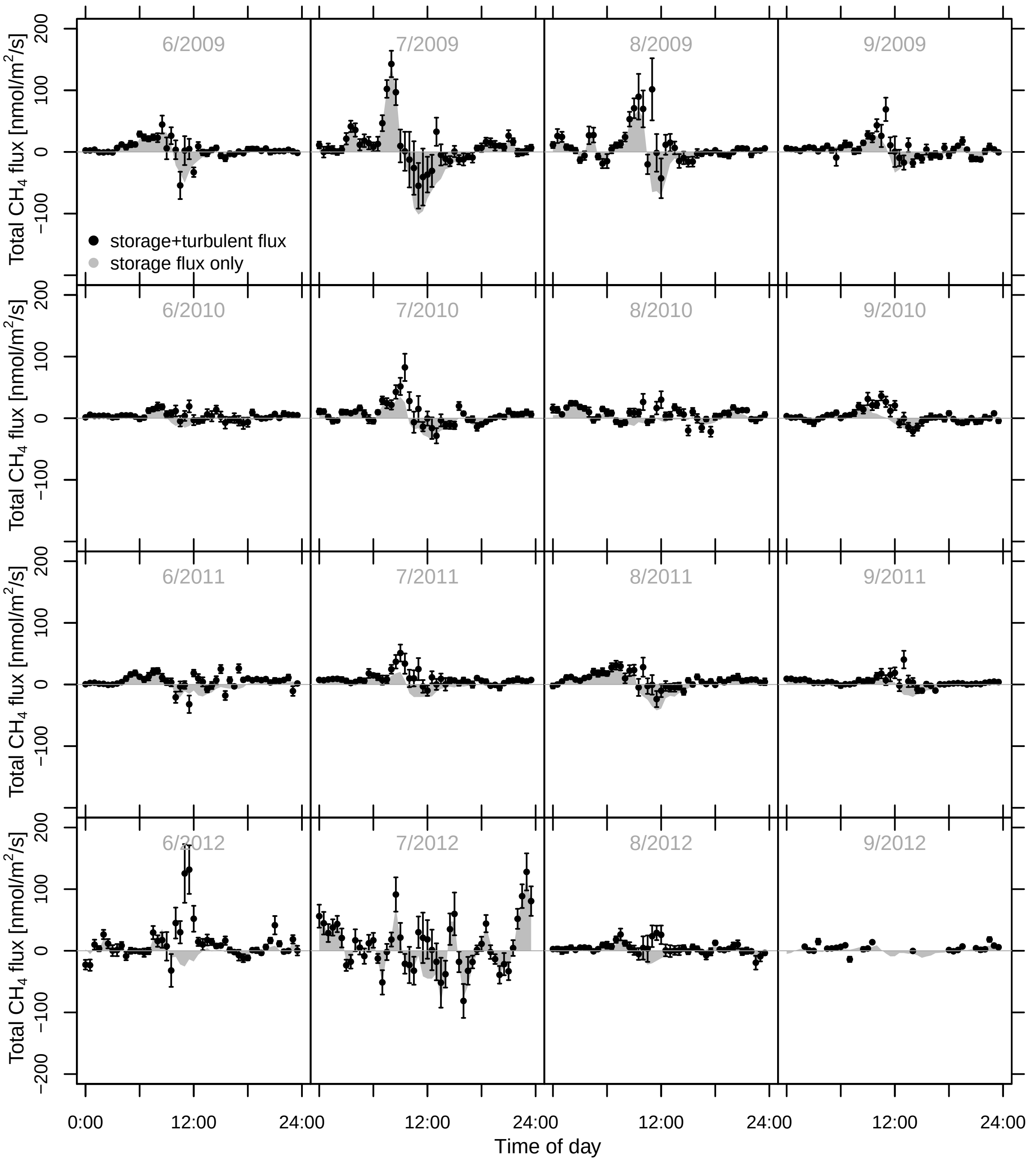

Fig. 9. Diurnal cycle of the total CH_4 flux estimate with standard deviation of the mean for all summer months in black: the grey area indicates the storage flux component.

magnitudes of CH_4 fluxes vary widely and depend on measurement type, temperature, water level and topography. Aircraft measurements in Siberia give 3 to 106 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 nmol $(m^2\,s)^{-1}$ (Rask et al., 2002). Modified Bowen ratio method at a tall tower in the boreal US give summer fluxes of 17.4 ± 10.4 nmol $(m^2\,s)^{-1}$ (Werner et al., 2003). Finally, eddy measurements show typical summer emissions of 2.5 nmol $(m^2\,s)^{-1}$ in a Finnish boreal fen (Rinne et al., 2007). Our data represent a case in point.

The most remarkable feature occurs during the morning transition, when estimated CH_4 fluxes show values up to 130 nmol $(m^2\,s)^{-1}$ ($\sim$ 180 mg $(m^2\,day)^{-1}$). The most

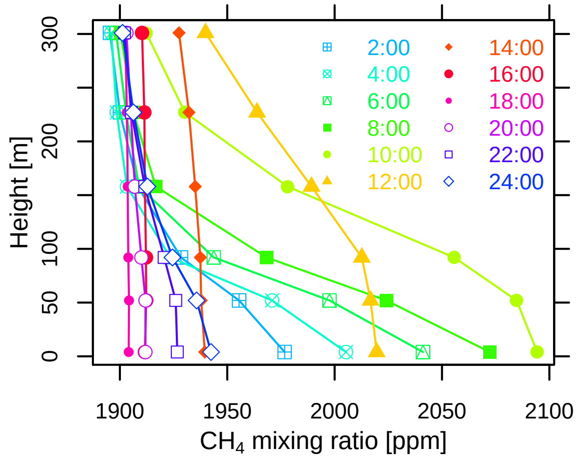

Fig. 10. Diurnal variation of the CH_4 mixing ratio at ZOTTO tower in July 2009.

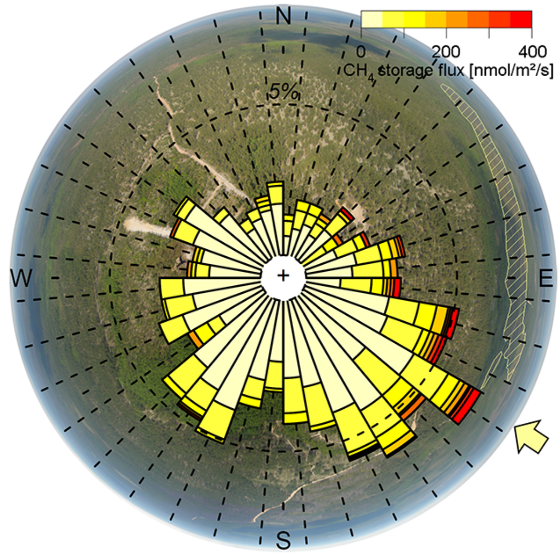

Fig. 11. Top view of ZOTTO centered on the tower with overlaid nighttime storage flux estimates (23:00 to 08:00 KRAT; > 30 nmol $(m^2\,s)^{-1}$ only) vs. wind direction for all summer months June–September of 2009–2011: the overall lengths of the petals show how often a flux from this direction is measured,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

probable reason for this is the topography around the tower. The tower is located on a small hill and is surrounded by bogs. During nighttime, 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 are close to zero around midnight. With sunrise, the air layers mix up to higher altitudes and pass by the 301 m tower. Rising air from below to the height of the tower results in a large positive flux signal, which is compensated by a negative flux when the air is ventilated on top of the control volume (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 25 km east of the station in the case of CO_2 (van der Molen and Dolman, 2007). Because CH_4 fluxes show heterogeneities on an 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 the northeast and east, where the closest bog to the station is located (yellow hatched area). Another large mire is located to the southeast, which probably explains 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) is a very local effect and represents the integral flux of the nearby bog during the whole night (23:00–06:30), we obtain CH_4 fluxes up to 27.4 nmol $(m^2\,s)^{-1}$ in July 2009. Future CH_4 flux measurements (starting after repair in the 2013 vegetation season) will facilitate further investigation.

4 Summary and conclusion

We estimate ecosystem fluxes from concentration gradients from six height levels (301, 228, 158, 92, 52 and 4 m) at the ZOTTO station for the period beginning in 2009, when neither aircraft nor eddy covariance data were available. We gain the most reliable information during nighttime, 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 nighttime fluxes (23:00

to 04:00) are $2.7 \pm 1.1\,\mu mol\,(m^2\,s)^{-1}$ 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 rises up and passes by the tower due to the onset of air mixing at sunrise. The nighttime CH_4 fluxes (23:00 to 04:00) are $5.6 \pm 4.5\,nmol\,(m^2\,s)^{-1}$ in the summer months, and are feasible when compared 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).

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

Supplementary material related to this article is available online at http://www.biogeosciences.net/11/2055/2014/bg-11-2055-2014-supplement.pdf.

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