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A decade of carbon, water and energy flux measurements of an old spruce forest at the Anchor Station Tharandt

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ABSTRACT

At Tharandt/Germany eddy covariance (EC) measurements of carbon dioxide and heat fluxes are performed above an old spruce forest since 1996. The last ten years cover almost all meteorological extremes observed during the last 45 years: the coldest and warmest year with mean air temperature of 6.1°C (1996) and 9.6°C (2000) as well as the fourth wettest and the driest year with a precipitation of 1098 mm (2002) and 501 mm (2003), respectively. In general, the observed annual carbon net ecosystem exchange (*NEE*) indicates a high net sink from -395 g C m^{-2} a^{-1} (2003) to -698 g C m^{-2} a^{-1} (1999) with a coefficient of variation $c_v = 16.6\%$. The yearly evapotranspiration (*ET*) has a lower interannual variability ($c_v = 9.5\%$) between 389 mm (2003) and 537 mm (2000). The influence of flux correction and gap filling on the amount of annual *NEE* and *ET* is considerable. Using different methods of gap filling (non-linear regressions, mean diurnal courses) yields annual *NEE* totals that differ by up to 18%.

Consistency analysis regarding energy balance closure, comparisons with independent soil respiration and biomass increment measurements indicate reliability of the fluxes. The average gap of the energy balance is 15% of the available energy based on regression slope with an intercept of 3 to 16 W m^{-2}, but around zero for annual flux ratios. Between 47% and 63% of the net ecosystem productivity was fixed above ground according to up-scaled tree ring data and forest inventories, respectively. Chamber measurements of soil respiration yield up to 90% of nighttime EC based total ecosystem respiration. Thus, we conclude that the EC based flux represents an upper limit of the C sink at the site.

1. Introduction

Facing the increasing CO_2 concentration in the atmosphere and its relevance for the earth's climate system, new and accurate information is needed on the carbon exchange of forest ecosystems at all latitudes and its temporal variation. Continuous measurements of atmospheric fluxes give the possibility to study the exchange processes with the atmosphere and the carbon storage within the ecosystem as well as the ecosystems reactions on meteorological and hydrological conditions that are likely to change in the future (Lindroth et al., 1998; Baldocchi et al., 2001).

Based on the eddy covariance (EC) technique, the carbon dioxide and heat fluxes of different ecosystems has been measured throughout the world (e.g. Wofsy et al., 1993; Knohl et al., 2003; Saigusa et al., 2005). Established in 1996, EUROFLUX was the first continental wide flux network with the aim to investigate the long-term biospheric exchanges of carbon, water and energy of European forests according to commonly agreed standards (Aubinet et al., 2000; Valentini et al., 2000). The measurements at the Anchor Station Tharandt within EUROFLUX and the following projects CARBOEUROFLUX and CARBOEUROPE-IP are the basis for this study. Its aim is to show budgets of carbon dioxide and water vapour based on long-term EC measurements, the influence of correction and gap filling procedures on the annual sums as well as a check of the carbon balance using forest inventories and independent increment data.

2. Material and methods

2.1. Site description

The Anchor Station Tharandt (50°57′49″N, 13°34′01″E, 380 m a.s.l.) is located in the eastern part of a large forested area (60 km^2) near the city of Tharandt, about 25 km SW of Dresden. This forest has a long history of forestry documentation as well as meteorological and hydrological measurements: (i) climate data since the 1950s, (ii) hydrological data of the Wernersbach

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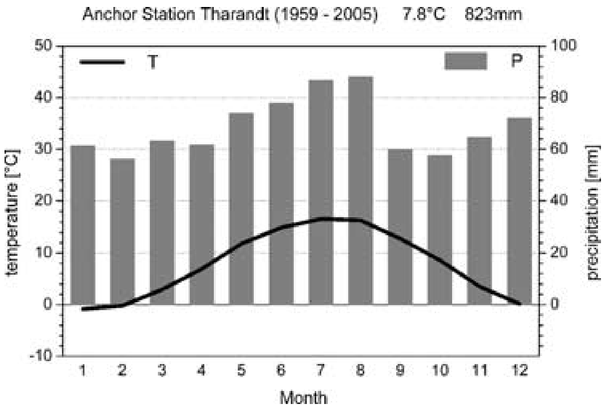

Fig. 1. Mean monthly values of air temperature and precipitation at the Anchor Station Tharandt in the period 1959–2005 [mean annual precipitation: 823 mm, mean annual air temperature: 7.8°C, maximum daily precipitation: 228 mm (12 August 2002), maximum daily air temperature: 28.3°C (13 August 2003), minimum daily air temperature: −20.6°C (13 January 1987)].

catchment (4.6 km^2) since 1968 and (iii) continuous flux measurements by EC technique since 1996.

The site is located in the suboceanic/subcontinental climate. According to the long-term records of the adjacent weather station (1959–2005), the mean annual air temperature is 7.8°C (maximum and minimum annual means are 9.4°C, 2000 and 6.0°C, 1996, respectively), the mean annual precipitation is 823 mm (maximum and minimum yearly sums are 1287 mm, 1981 and 501 mm, 2003, respectively). The annual course of precipitation has a convective summer maximum and a weaker frontal maximum in winter. Generally, the area is subject to episodic summer droughts with a re-occurrence of about 10 yr (see e.g., model results of Churkina et al., 2003); during the investigated period, an extremely dry summer occurred in 2003. The main wind direction is SW. For more details on the average climate, see Fig. 1.

The spruce stand at the Anchor Station Tharandt was established by seeding in 1887. Besides the dominating spruce trees, some additional trees species are present: in the vicinity of the measurement tower, the species of the main canopy are composed of 87% coniferous evergreen (72% *Picea abies*, 15% *Pinus sylvestris*) and 13% deciduous (10% *Larix decidua*, 1% *Betula spec.* and 2% others). The tree density is 477 trees ha^{-1}, the above ground biomass 213 t ha^{-1}, the leaf area index is 7.6 and the mean canopy height is 26.5 m. The mean breast height diameter is 33 cm. The ground is mainly covered by young *Fagus sylvatica* (20%) and *Deschampsia flexuosa* (50%). All values are taken from a special inventory of 1999 within a radius of 500 m around the tower.

In the vicinity of the tower, there are two small not forested areas. In western direction, there is an opening of about 1 ha covered mainly with grass (location of the climate station), to the North, there are some laboratories of the forestry department (covering about 0.5 ha). A small strip of young 24 yr old trees (3.5 ha) composed of spruce (*Picea abies*) and birch (*Betula spec.*) is located in eastern direction. Besides these inhomogeneities, there are no fetch restrictions by stand inhomogeneity; topography is limiting the fetch to about 500 m in two small sectors only (Northeast, Southeast). From footprint investigations, the site is considered to be reasonably homogeneous to represent the fluxes of the spruce dominated area of the Tharandt forest (Mellmann et al., 2003; Rebmann et al., 2005). In April 2002, there was a thinning at the site resulting in a reduction of tree density, leaf area index (LAF) and basal area (30, 11 and 14%, respectively) as well as in an increase of mean diameter at breast height (11%, Gerold, 2004).

The soil is characterized by a loamy skeleton podsol-brown earth which is typical for the lower parts of the eastern Ore Mountains (Nebe and Wenk, 1997). The soil depth is around 1 m, the depth of the main rooting zone is 35 cm. The soil water field capacity and the wilting point were estimated to 16 Vol-% and 7 Vol-%, respectively. The area is gently sloped facing south (2°).

2.2. Measurements

The eddy covariance measurements of fluxes of carbon dioxide, momentum, latent and sensible heat were established in July 1996 on top of the tower (42 m above ground) using an ultrasonic anemometer (sonic; Gill Solent R2, Gill Instruments, Lymington, UK) and a closed-path infrared gas analyser (IRGA; LiCor 6262, LiCor Inc., Lincoln, NE, USA). The sampling air is sucked through a 63 m tube (inner diameter of 10.7 mm) to the ground with a flow rate of 60 l min^{-1}. A second smaller pump provides the air to the IRGA using a bypass of the main stream (inner diameter 4 mm, flow rate 4–6 l min^{-1}). Two air filters (Gelman ACRO50 PTFE, Ann Arbor, MI, USA) with 1 μm pore size at the top of the tower (replaced weekly) and close to the IRGA are used. At the measurement height, a second sonic (METEK, USA1, Elmshorn, Germany) provides redundant measurements of momentum and sensible heat flux. The short- and long-wave radiation components of both hemispheres (in and outgoing) are measured separately in 37 m above ground by a combination of a Schulze net radiometer (Dr. Lange, Germany), a Sonntag type up- and downlooking pyranometer (Lambrecht, Göttingen, Germany), a pyrgeometer (Eppley, Newport, RI, USA) for down-welling longwave and a KT-15 infrared temperature probe (Heimann, Wiesbaden, Germany) for up-welling long-wave radiation. The photosynthetic photon flux density (*PPFD*) is available in four heights within and above the canopy. Measurements of other meteorological variables (humidity, temperature and wind speed) are also available in different heights above ground. Further, there is an 8 point vertical profile of the CO_2 and H_2O concentration available (0.2, 0.5, 2, 8, 26, 33, 37 and 40 m above ground). The IRGAs used for flux as well as gradient measurements were calibrated weekly.

Close to the tower, there are several soil and canopy related measurements. Soil moisture (by TDR, in 10 cm depth) and gradients of soil temperature (in six depths from 2 to 50 cm) are measured continuously. Additionally, there are periodic measurements (two times per week) of the soil moisture by TDR in nine depths (from 20 to 100 cm). Soil respiration is continuously measured for several months each year by open dynamic chambers since 2000. The setup is located around 50 m south of the tower and consists of five chambers. Each chamber is used for three plots located close together. So in total 15 measurement plots are available of which five are operated simultaneously. The plots are placed on bare soil as well as on soil covered with *Deschampsia flexuosa*. The chambers are relocated two to three times per week. The difference of the carbon dioxide concentration outside and inside the soil chamber is measured with a BINOS gas analyser (Rosemount Inc., Chanhassen, MN, USA) and the flow rate is recorded using a mass flow controller (MKS Instruments, Wilmington, MA, USA). The chamber design is optimized regarding a prevention of underpressure inside the chamber. A water vapour trap is inserted to keep the air stream free of water vapour (more details in Subke, 2002).

Sap flow measurements using the Granier method and litter fall observations are also available at the site, as well as phenological observations and tree ring analysis. However, this study will concentrate on the EC flux and utilises the above mentioned methods to provide auxiliary data.

The site was part of the spruce forest analysis in Bernhofer et al. (2003b) and had been included in many across site publications (e.g. Valentini et al., 2000; Falge et al., 2001; Ciais et al., 2005). In 1988, 1999 and 2004, forest inventories had been conducted and analysed within a 500 m radius around the tower. They provided the basis for footprint area weighted biomass parameters (Table 1). Under unstable conditions, 48% of the fluxes have their source in two plots of 13 ha around the tower. These plots are located in S and SW direction and characterized by very similar stand structure as given in Table 1 for the total footprint area of 78.5 ha. This is due to the weighting of the stand structure variables by the footprint of the fluxes. With the usual u^* (friction velocity) criterion (see Falge et al., 2001), this holds also for the stable conditions utilized for carbon and water budgeting. Rebmann et al. (2005) concluded that 80% of the fluxes measured are representing the target land use. Measurement campaigns mainly focussed on the role of advective fluxes at the site were realised in autumn 2001 (Feigenwinter et al., 2004) and from May to October 2003.

Table 1. Mean stand and biomass parameters at the Anchor Station Tharandt, weighted for the footprint area (78.5 ha), according to two forest inventories 1988 and 1999 (after Mellmann et al., 2003)

	1988	1999
Tree age [yr]	97	108
Canopy height [m]	25.5	26.5
Tree density [n ha^{-1}]	483	477
Tree diameter at breast height [cm]	29	33
Leaf Area Index [m^2 m^{-2}]	5.8	7.6
Basal area [m^2 ha^{-1}]	28.1	35.8
Above-ground biomass [kg m^{-2}]	16.8	21.3

2.3. Flux calculation and correction

Based on the data logging frequency of 20.8 Hz values of the sonic and IRGA covariances, standard deviations and mean values were calculated on a half hourly basis by block averaging (no detrending applied). During post-processing outliers (values outside a plausible range) are removed and the time lag between the sonic and IRGA measurements is calculated and taken into account. The latter is done by maximising the regression coefficient between the vertical wind speed and the concentrations of carbon dioxide and water vapour, respectively. If there is no plausible lag value detected within a defined range the previous value is used. Typical daytime lag values are 6 s for CO_2 and 7 s for H_2O. Downward directed fluxes have negative signs. The turbulent fluxes of carbon dioxide (F_c), water vapour ($L.E$) and sensible heat (H) as well as the friction velocity (u^*) were claculated as

$$F_c = \rho \overline{w'\rho_c'}, \quad (1)$$

$$L.E = L\overline{w'\rho_a'}, \quad (2)$$

$$H = \rho c_p \overline{w'T_s'}, \quad (3)$$

$$u* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}, \quad (4)$$

where ρ is the density of dry air, c_p the specific heat capacity of dry air at constant pressure, L the latent heat of vaporization; u, v, w are the horizontal and vertical wind velocity components, ρ_c and ρ_a are the carbon dioxide and the water vapour concentration, respectively. Overbars denote time averages and primes indicate departures therefrom.

In general, the fluxes are calculated and corrected according to the EUROFLUX methodology (Aubinet et al., 2000). A two-dimensional (2-D) rotation was applied (Kaimal and Finnigan, 1994, McMillen, 1988) to the carbon dioxide and heat fluxes. The third rotation was applied in order to nullify the lateral momentum flux density, changing the flux value in very few cases only. The sensible heat flux is corrected for humidity and cross wind according to Schotanus et al. (1983). The correction for density fluctuations proposed by Webb et al. (1980) was not considered due to the considerable damping of such fluctuations within the long tube. According to Rannik et al. (1997), this can be done if the tube length is at least 1000 times longer than the tube diameter. This requirement is fulfilled at our site. The damping loss in the high-frequency part of the cospectra of carbon dioxide and water vapour flux was corrected by a similar method as proposed by Eugster and Senn (1995): assuming an undamped sensible heat flux, the correction factors were grouped in six stability classes. For unstable stratification the corrections amount on an average to +20% (carbon dioxide flux) and +26% (water vapour flux). Under stable conditions, the respective values are +37% and +45% (Bernhofer et al., 2003a). The latter are typically not relevant for carbon and water budgeting as considerable stable conditions are restricted to low u^* values at night and are, therefore, replaced by modelled values derived from turbulent nights (u^* correction).

The soil respiration rate (*SR*) was calculated using the carbon dioxide concentration difference $\Delta\,\rho_c$ at the end of a 5 min measurement cycle (to guarantee steady-state condition) as follows:

$$SR = \frac{\rho Q \Delta\rho_c}{MA}, \tag{5}$$

where Q is the flow rate, M the molar mass of dry air and A the surface area of the chamber (Subke, 2002).

2.4. Modelling the CO_Θ exchange

The carbon net ecosystem exchange (*NEE*) is the sum of the turbulent carbon dioxide flux F_c and the flux due to the temporal change of the carbon dioxide storage S_c below the level of the EC measurements. For calculating the S_c on a half hourly basis, a method using eight layers ($S_{c,8}$) was compared with a single layer method using the concentration measurements in the EC level 42 m above ground only ($S_{c,1}$). Regression analysis showed very similar results. Based on 2001, the $S_{c,1}$ is only 1% less than $S_{c,8}$ ($r^2 = 0.76$). The reasons are (i) the more or less parallel diurnal courses of the concentrations in the five upper levels and (ii) the small height of the three levels near the ground, which lead to a corresponding small contribution of their storage change to the overall storage change. So, for further modelling $S_{c,1}$ was used to address the *NEE*. The other storage change components (latent and sensible heat) were calculated in an analogue way. The heat storage change within the biomass was determined using the mean bole temperature of a selected tree (thermocouples in different heights and directions). Two heat flux plates at 1 cm depth are used to measure the soil heat flux.

The modelling of the *NEE* on a half hourly basis is mainly used for data gap filling and u^* correction (replacement of measured nighttime *NEE* values by modelled values during periods of insufficient turbulence). For daytime conditions, (*PPFD* greater than 5 μmol m^{-2} s^{-1}), a Michaelis–Menten approach was used (Falge et al., 2001):

$$NEE_{\text{daytime}} = -\left(\frac{a'^{*}PPFD^{*}NEE_{\text{sat}}}{NEE_{\text{sat}} + a'^{*}PPFD} - R_{\text{day}}\right), \tag{6}$$

where a' is the light use efficiency, NEE_{sat}, the *NEE* at light saturation and R_{day}, the daytime respiration. To parameterize (6), the half hourly data set was split in 2 K classes of air temperature (beside the ranges of lower than 0°C and greater than 24°C). The nighttime values (*PPFD* lower than 5 μmol m^{-2} s^{-1}) were modelled with an exponential dependency on soil temperature T_s in 2 cm depth:

$$NEE_{\text{nighttime}} = R_{10}e^{\frac{A}{B-C} - \frac{A}{T_s - C}}, \tag{7}$$

where R_{10} express the total ecosystem respiration at 283 K and A, B and C are constants according to Lloyd and Taylor (1994) and are 308.56 K, 283.15 K and 227.13 K, respectively. The R_{10} value was fitted using bi-monthly half hourly data sets to consider seasonal changes of biological activity (e.g. due to litter fall) and soil moisture change. Only at night, a u^* criterion was defined to exclude periods of insufficient turbulence. To do this, the annual data sets have been split by a stepwise increase of the u^* threshold (in classes of 0.05 m s^{-1}) and R_{10} of (7) was parameterized for each data set. Typically R_{10} values increase with increasing u^* threshold. The lowest u^* threshold where this dependency ends is defined as the critical u^* value u^*_c. For individual years, u^*_c values range between 0.3 m s^{-1} (1997) and 0.45 m s^{-1} (2003). All half hourly values below this threshold were excluded for the parameterization of (7). Additionally, several modifications of data gap filling methods (non-linear regressions, mean diurnal courses MDC with 14-d moving average) were tested to fill the gaps in the *NEE* data. The MDC method was applied on flux values with no turbulence restrictions only (above u^*_c at night). All other values were filled by the respective value of the MDC.

3. Results

3.1. Annual balances

Since the start of the EC measurements at the Anchor Station Tharandt, 10 yr of full half hourly data sets (with moderate amounts of data gaps) are available until now. The inevitable gaps include failure of the instruments, inadequate nitrogen supply, tube leakage or power failure as well as insufficient turbulence during nighttime. The records of the half hourly *NEE* values were filled using (6) and (7). Over the years, the frequency of the gaps due to technical failures amount to values between 3% (2004) and 26% (1997). The gaps caused by insufficient nighttime turbulence range between 16% (1997) and 23% (2003) and are typically more prominent than the first type. The total ecosystem respiration (*TER*) was calculated as sum of measured ($u^* > u^*_c$) and modelled ($u^* < u^*_c$) nighttime *NEE* as well as the modelled daytime respiration part using (7). The gross primary productivity (*GPP)* is the sum of net ecosystem productivity (*NEP)* (*NEP* = −*NEE*) and *TER*.

Table 2 lists the annual values of selected variables to characterize the carbon dioxide exchange and meteorological conditions from 1996 to 2005. The annual *NEP* values range between 395 g Cm^{-2} (2003) and 698 g Cm^{-2} (1999). Based on the whole 9-yr-period since 1997, 30% of the *GPP* are fixed as net carbon sink, whereas the lowest and highest ratio were observed in the years with the lowest (2003, 24%) and the highest *NEE* (1999,

Table 2. Yearly sums of carbon net ecosystem productivity *NEP*, gross primary productivity *GPP*, total ecosystem respiration *TER* [g C m^{-2}], sum of evapotranspiration *ET* [mm], photosynthetic photon flux density *PPFD* [kmol m^{-2}] and precipitation *P* [mm], mean air temperature T_{air} [°C], Bowen ratio β as well as mean values and coefficient of variation c_v at the Anchor Station Tharandt 1996–2005

Year	NEP	GPP	TER	ET	PPFD	T_{air}	P	β
1996	448	1590	1142	-	6.8	6.1	771	-
1997	564	1860	1296	485	8.0	8.3	714	0.66
1998	573	1795	1221	499	7.1	8.5	909	0.56
1999	698	2095	1397	518	7.4	9.0	826	0.59
2000	650	2034	1384	537	7.5	9.6	803	0.59
2001	559	1694	1135	487	6.3	8.3	938	0.53
2002	544	1874	1329	445	6.9	9.0	1098	0.64
2003	395	1671	1276	389	7.9	9.0	501	1.16
2004	473	1868	1395	438	7.2	8.3	874	0.76
2005	597	1970	1373	478	7.1	8.4	898	0.72
Mean	550	1845	1295	475	7.2	8.5	833	0.69*
c_v (%)	16.6	8.8	7.7	9.5	7.1	11.0	18.9	27.7*

*For consistency within the table mean β and c_v are calculated from single years β.

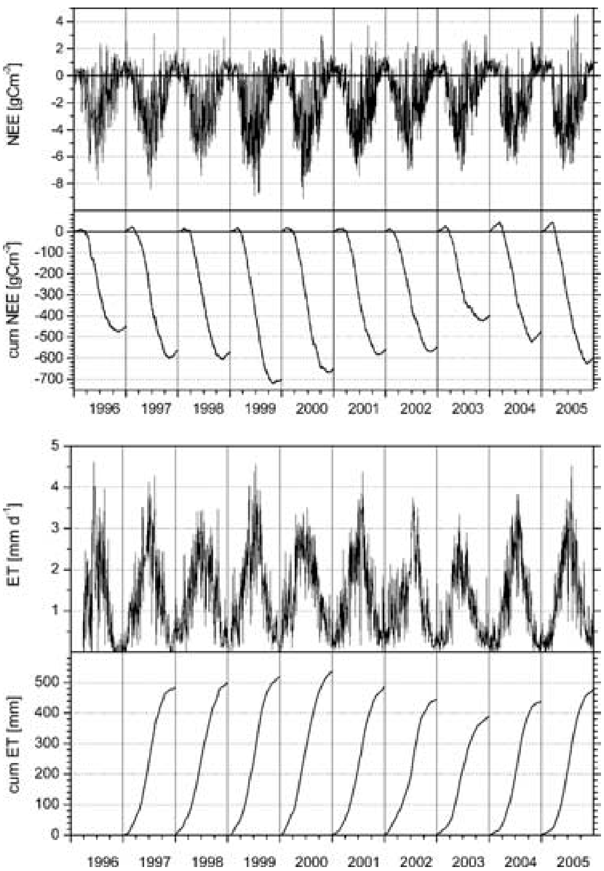

Fig. 2. Daily, as well as yearly cumulated values of the carbon *NEE* (top) and the *ET*, based on latent heat fluxes (bottom) at the Anchor Station Tharandt 1996–2005.

33%), respectively (Grünwald, 2003). In Fig. 2, the interannual and annual variability of *NEE* and evapotranspiration (*ET)* are shown on a daily basis for the period 1996–2005. The annual *ET* and *H* values were calculated as the sum of measured fluxes and gap filled values using mean diurnal courses (14-d moving average). Concerning the nighttime data only half hourly values under sufficient turbulence conditions have been considered to ensure a consistent data set with respect to the *NEE* data. Over the years, the gap frequency is similar to the carbon fluxes. On an annual basis, the evapotranspiration shows a smaller variance (expressed by the coefficient of variation $c_v = 9.5\%$) than the carbon net ecosystem exchange ($c_v = 16.6\%$) with yearly sums from 389 mm (2003) to 537 mm (2000). The Bowen ratio varies around 0.6 to 0.7 but c_v is considerably increased by the single year 2003 with ß = 1.16 (2003).

From above, it is obvious that the annual balances of *NEE* are results of the measurements including the application of different flux corrections and gap filling procedures. These fluxes should be still considered as measured as they are based on gap filling techniques that utilize measured fluxes only. However, a considerable uncertainty exists that is addressed in the following section. For a better understanding of the quantitative influences of the correction steps, the annual *NEE* is shown (i) without flux corrections (NEE_{uncorr}), (ii) corrected for the flux losses (see Section 2.3), but without gap filling / u^* correction (NEE_{corr}) and (iii) with additional application of gap filling / u^* correction (NEE_{final}). The respective yearly values are given in Table 3. They are typically based on about 65% of maximum possible data. So, 35% are replaced by gap filling with the majority at night. Comparing NEE_{corr} with NEE_{uncorr} , the annual *NEE* values increase between 24% (2004) and 44% (2002). Part of this variability arises from the seasonal timing of larger gaps in certain years. The application of the gap filling and u^* correction to avoid an underestimation of the nighttime *NEE* results in a reduction of the NEE_{final} from 6% (1998) to 22% (2003) compared with the NEE_{corr}. Besides the higher occurrence of calm nights in 2003, the large correction due to the u^* criterion is also caused by the high u^*_c value of 0.45 m s^{-1} for 2003 (but assuming a u^*_c of 0.3 m s^{-1} would result in a similar reduction of 19%).

3.2. Uncertainty of the annual carbon exchange

To get an insight into the uncertainty of the annual carbon exchange given in Table 2, we tested its sensitivity to modified procedures of gap filling and *NEP*, *TER* and *GPP* calculation. Our reference method is gap filling and nighttime u^* correction based on non-linear regressions according to (6) and (7), as well as use of the nighttime fluxes and their dependency on soil

Table 3. Yearly sums of the *NEE* for different correction steps: (i) uncorrected fluxes NEE_{uncorr}, (ii) corrected for flux losses but without gap filling / u* correction NEE_{corr} and (iii) with additional application of gap filling / u* correction NEE_{final} as well as the proportion of measured fluxes on half hourly basis used for the calculation of NEE_{final} at the Anchor Station Tharandt for 1997–2005

year	NEE_{uncorr}	NEE_{corr}	NEE_{final}	Proportion of measured fluxes (%)
1997	−460	−621	−564	59
1998	−478	−613	−573	62
1999	−617	−791	−698	68
2000	−557	−749	−650	64
2001	−479	−626	−559	68
2002	−430	−618	−544	65
2003	−405	−504	−395	64
2004	−447	−553	−473	73
2005	−493	−640	−597	69

temperature to calculate the daytime respiration. This method has been modified and following changes had been tested in comparison with the reference method: (i) to apply the u^* correction also to the daytime fluxes, (ii) to use R_{day} from (6) dependent on air temperature to calculate the daytime respiration for *TER* and *GPP* balances and (iii) use R_{day} for daytime respiration and to fill the missing nighttime fluxes. To understand the effect of the modified procedures on *NEP*, *TER* and *GPP,* first the differences of daytime and nighttime *TER* and daytime *NEP* are discussed. The daytime *TER* is mainly reduced if R_{day} of (6) is used instead of (7) with differences from -183 g C m^{-2} a^{-1} (2003) to $+16$ g Cm^{-2} a^{-1} (1998). The typical behaviour of R_{day} is—in contrast to (7)—an increase with increasing temperature until a saturation level is reached. So, during years with frequent high temperatures (e.g. 2003) and during daytime especially the respiration components are reduced using (ii) and (iii) compared with the reference method. A similar effect on nighttime *TER* by using (iii) is observed. It is reduced in a range of -7 g Cm^{-2} a^{-1} (2001) to -58 g Cm^{-2} a^{-1} (2003). Daytime *NEP* increases slightly by the daytime u* correction [from $+8$ g Cm^{-2} a^{-1} (1997) to $+27$ g Cm^{-2} a^{-1} (1999)]. This indicates the small turbulence restrictions during daytime. Figure 3 depicts the resulting differences of *NEP*, *TER* and *GPP* by using the three modifications. *NEP* is increased in a range of $+7$ g Cm^{-2} a^{-1} (1997, method (i)) to $+58$ g Cm^{-2} a^{-1} (2003, (iii)). The corresponding uncertainty is 1% to 15%. *TER* changes between $+16$ g Cm^{-2} a^{-1} (1998, (ii), +1%) and -241 g Cm^{-2} a^{-1} (2003, (iii), −19%). *GPP* is increased up to +2% using method (i) but typically reduced using (ii) and (iii) (up to −11%).

Additionally, mean diurnal courses have been tested to fill data gaps of the *NEP* according to the procedure outlined in Section 2.4. The annual values are changed by −4% (2005) to +18% (1998) compared to the reference method. The years of the highest and lowest annual sums are also 1999 (765 g Cm^{-2}, +10%) and 2003 (423 g Cm^{-2}, +7%), respectively.

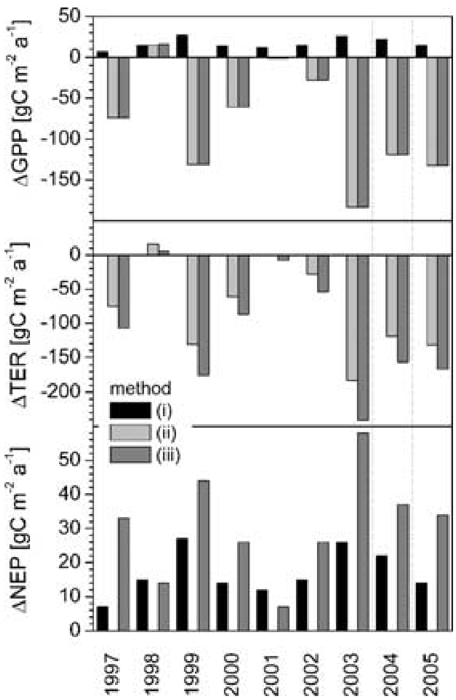

Fig. 3. Differences of *NEP*, *TER* and *GPP* on an annual scale comparing three different methods with the reference method for gap filling (for more details refer to the text) for the period 1997–2005, (i) to apply the u^* correction also to the daytime fluxes, (ii) to use R_{day} dependent on air temperature to calculate the daytime respiration for *TER* and *GPP* balances and (iii) use R_{day} for daytime respiration and to fill the missing nighttime fluxes.

3.3. Consistency analysis of energy and carbon balance

Several possibilities exist to test the internal and external consistency of the EC measurements. Internal tests are spectral and turbulence tests (e.g. Foken and Wichura, 1996) and can be utilized to identify periods of insufficient turbulence or instationarity.

Rebmann et al. (2005) used internal tests to check the Tharandt data (among several CARBOEUROPE sites) with no obvious shortcomings, so here we look at external tests. They are: the energy balance closure, quantification of advection and comparisons of the *NEE* data with independent biomass increment data and soil respiration rates. Feigenwinter et al. (2004) report a considerable contribution of advective fluxes to carbon budgets at certain times of the day, but also that vertical and horizontal advection cancel each other in their test period in late summer of 2001 at the Anchor Station Tharandt. Therefore and due to the limited time period covered, we concentrate on the other methods here. All are based on conservation laws (energy and matter), but only the energy balance and the direct soil measurements have the same time resolution as the EC measurements. Forest inventory or biomass increment data are much coarser in time and provide only small data sets for comparison.

The gap in the energy balance closure is a suitable first indicator of the consistency of flux measurements. Large closure gaps might also point toward effects of advection due to topography or heterogeneity of the canopy. Based on half hourly values (data with insufficient turbulence at nighttime excluded), the parameters of a linear regression between the available energy (sum of net radiation and heat storage changes) and the sum of the turbulent heat fluxes were calculated for each year. The slope and the intercept of this regression vary between 0.76 (1998) and 0.94 (2000) and 2.6 (2004) and 16.2 (2000), respectively. The r^2 value is up to 0.90 (refer to Table 4). The flux corrections improve the energy balance closure. For instance, the parameter of the year 2000 before and after applying the flux corrections are 0.77 and 0.90 (slope), −10.8 and 16.2 (intercept), 0.82 and 0.90 (regression coefficient), respectively. The negative intercept by using uncorrected fluxes is caused by strong negative sensible heat flux values during high wind speed. This special effect of the flux sonic (Gill Solent R2) was corrected using redundant measurements with a second sonic (METEK, USA1). The intercept increases if the storage terms are not taken into consideration (connected with a reduced slope). Using the annual ratio between the sum of the turbulent fluxes and the available energy yields different results (see Table 4). This ratio ranges between 0.87 (2004) and 1.11 (2000), similar as reported by Wilson et al. (2002). Forcing the regression through the origin (assuming a zero intercept) reduce the r^2 value only marginally and leads to very similar values of the annual ratio and regression slope. Furthermore, during nighttime (or winter) the underestimation of the sensible heat flux is usually higher than during daytime (or summer). Thus, combining positive and negative heat fluxes reduces the closure gap for long-term balances, an argument similar to Gay et al. (1996).

Table 4. Annual energy balance closure according to a linear regression (slope, intercept and r^2 value) and the ratio between the sum of the turbulent heat fluxes and the available energy (sum of net radiation and heat storage changes) at the Anchor Station Tharandt for 1997– 2005

year	slope	intercept	r^2	*(H+L.E)/AE*
1997	0.78	11.6	0.86	0.91
1998	0.76	15.9	0.83	0.99
1999	0.89	10.0	0.90	1.00
2000	0.90	16.2	0.90	1.11
2001	0.87	10.1	0.88	1.00
2002	0.81	12.0	0.84	0.97
2003	0.84	6.7	0.88	0.91
2004	0.84	2.6	0.90	0.87
2005	0.94	10.7	0.88	1.08

An independent check of the carbon balance at the site is possible by using increment data based on tree ring analysis and forest inventories (Gerold, 2004; Köstner et al., 2006). Annual above-ground net primary production NPP_{ag} (without root growth) determined from radial stem growth and tree harvests in the vicinity of the tower as well as from forest inventories within the total source area (500 m radius) represented on average 47–63% of *NEP*. Together with preliminary estimates of soil carbon change (based on litter fall measurements) and of root growth, this ratio increases to 81–104% (Köstner, 2006, personal communication).

To compare the total respiration *TER* with the independent measurements of the soil respiration, *SR* daily totals have been calculated if at least four of the five simultaneously measured plots and 80% of the half hourly values are available. Based on those criteria and snow free periods, 2003 and 2005 show the highest data availability (85 and 92 d, respectively). Comparing the *SR* with the (u^* corrected) *TER* the high proportion of the soil respiration to the overall respiration is noticeable. The respective ratio is 0.87 for the period of May to October 2003 and 0.93 for April to October 2005, respectively. During wintertime (without snow coverage), the *SR* is higher than the *TER* in general. Figure 4 depicts the temperature dependency of *SR* and *TER* based on daily values for 2005. Especially the low respiration rates show high relatively amounts of *SR*.

Ignoring the sampling problems in *SR* measurements (e.g. pressure differences in- and outside the chambers) as well as the different source areas of *SR* and *TER,* this could indicate an underestimation of the nighttime carbon fluxes by the EC method despite all corrections.

4. Discussion

Variable carbon exchange is typically attributed to changing environmental variables in time and site conditions in space (e.g. Valentini et al., 2003). The period since 1996 covers almost all meteorological extremes observed at the site during the last 45 years: the coldest year with annual mean air temperature of 6.1°C (1996), the warmest year with 9.6°C (2000), the fourth wettest year with an annual precipitation of 1098 mm

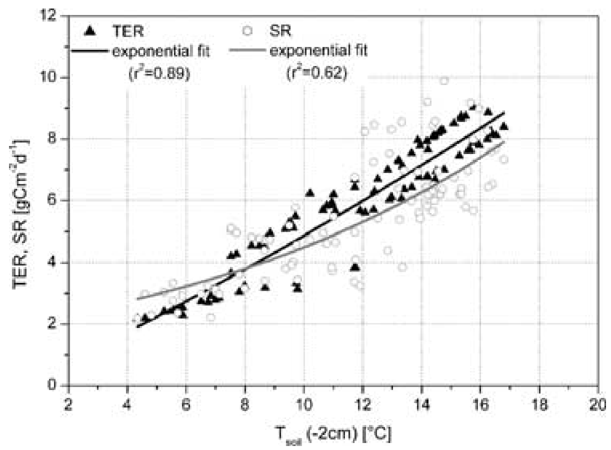

Fig. 4. Dependency of total ecosystem respiration *TER* and soil respiration *SR* on soil temperature T_{soil} in 2 cm depth at the Anchor Station Tharandt (daily values of the period April to October 2005).

(2002, Saxonian flood) and the driest year with 501 mm rainfall (2003).

For a single site, study forcing variables can be easily identified on a half-hourly basis. They are identical to the ones used for gap filling type models: *PPFD*, air and soil temperature (the soil moisture was not included in the routinely gap filling due to frequent data gaps in the past). The described variance by these simple predictors is typically high between half-hourly and monthly time scales. However, on an annual scale, there are no clear single dependencies between the carbon exchange components and the meteorological determinants. The best regression exists between phenological based observations and *NEP* and *GPP*, respectively. They are the dependencies of the *NEP* on the length of the vegetation period (determined as the mean period between leaf unfolding and leaf fall of different deciduous species) as well as of the *GPP* on the date of May shoot (Niemand et al., 2005) except for the dry year 2003. In contrast to pure climatological data (Reichstein et al., 2005), phenological data can obviously integrate properly for a multitude of factors but fail if extremes occur after the typical dates of the used phenophases (like in drought years). A global investigation of EC fluxes and phenology is on the other hand restricted by the necessary adaptation of the used phenological observations.

The dryness in 2003—characterized by a Bowen ratio value of 1.16 (the mean value of the whole period since 1997 is 0.69) and the lowest precipitation total (501 mm) since 1959—led to a drop in *NEE* and *ET* (especially during August and September). Also, most of the parameters of (6) and (7) show their lowest values in 2003 (especially NEE_{sat} and R_{day}). R_{10} decrease in late summer 2003 in a more distinct way than in the other years. This shows the sensitivity of annual totals to controlling factors, like water supply (see also Ciais et al., 2005) and explains a large part of the interannual variability.

In general, the observed annual *NEE* indicate a high net carbon sink strength of the site, with similar results at other spruce sites (e.g. Aberfeldy 1997: -624 g Cm^{-2} a^{-1}, Solling 1997: -470 g Cm^{-2} a^{-1}; Bernhofer et al., 2003b). The uncertainty of the annual *NEE* is less than 10% for different gap filling methods based on non-linear regression. Only the dry and hot year 2003 shows a maximum difference of 15%. This is mainly caused by gap filling during nighttime using different respiration models. In general, there is a good agreement between the different modelled respiration rates. In the high temperature range R_{day} shows a saturation level whereas the turbulent nighttime fluxes show an exponential increase. So, using R_{day} to model the nighttime fluxes or the daytime respiration part (instead of the exponential model) the respiration values are reduced which leads to an increased *NEP* and a decreased *GPP* especially in hot years. Alternatively, the method of the mean diurnal courses leads to moderate higher annual *NEP* values in general.

Additionally, there is a dependency of the annual *NEP* on the selected u^* threshold. A larger u_c^* value leads to a moderate decreased annual *NEP* sum and a higher portion of modelled values. The *NEP* of 2005 amounts to 699 g Cm^{-2} without u^* correction, and it is 597 g Cm^{-2} assuming an u_c^* value of 0.35 m s^{-1}. A further increase of the u_c^* to 1.0 m s^{-1} reduces the *NEP* to 593 g Cm^{-2} only. This supports the method that had been applied to derive u_c^*.

Looking at the range of the annual *NEP* numbers using the different gap filling procedures, our best estimates are on the lower limit. But comparisons with independent observations of the wood increment and the soil respiration suggest an underestimation of the respiration components by nighttime EC measurements despite all corrections. Assuming a reliable soil respiration measurement, there is an unusual high part of the *SR* within the *TER*. If we ignore the different spatial representativeness and other possible inconsistencies of both methods this suggests an overestimation of annual *NEP* by the EC method. Thus, we conclude that the EC based flux—gap filled with our reference method—represents an upper limit of the C sink at the site. Otherwise, nearly two third of the *NEP* could be found as carbon sink in the above-ground tree biomass (NPP_{ag}) deduced from forest inventories. The annual numbers of both methods show more or less parallel behaviour over the years (with the same minimum and maximum year 2003 and 1999, respectively; Köstner, 2006, personal communication). However, in addition with estimates of root growth and changes in soil carbon, up to 104% of the *NEP* was fixed in biomass and soil.

5. Conclusions

The decade of the EC measurements above an old spruce forest at the Anchor Station Tharandt shows high annual net carbon sinks between 400 g Cm^{-2} a^{-1} and 700 g Cm^{-2} a^{-1}. The reliability of the EC measurements at the site and of the EC flux correction procedures is documented by good data coverage and small energy balance closure gaps. The influence of different u^* corrections and the influence of gap filling procedures on *NEE* show in general a sensitivity of 10% for the annual carbon balance. Data filtering at a critical value of u^* remains an acceptable 'engineering method' that excludes periods of insufficient turbulence and limits the source area to the vicinity of the tower. It should be used as long as no simple and reliable methods exist to estimate non-turbulent fluxes.

Energy balance closure was acceptable for most years, especially when annual balances are addressed. Differences between annual ratios and the regression analysis based slope of the sum of the turbulent heat fluxes and the available energy are caused by a positive offset of the available energy at a zero total of turbulent heat fluxes. This points towards effects of storage fluxes or phase shifts between the energy balance components.

A reasonably good resemblance with independent measures was found, like biomass increment and soil chamber measurements. Nevertheless, a comparison of the total ecosystem respiration with the soil respiration shows a possible underestimation of the nighttime carbon fluxes despite all corrections. Around two thirds of the net ecosystem productivity could be found in the above-ground net primary productivity. So a remarkable fraction of *NEP* should represent the below-ground carbon sequestration (the residual carbon sink including potential uncertainties of *NEP*). On an annual scale (without water stress), the best predictors of *NEP* and *GPP* are phenology based variables (lengths of the growing season derived by observations of different deciduous species and May shoot of *picea abies*).

The results stress the necessity of long-term and redundant (or better supportive) measurements of carbon fluxes by different methods as well as to apply some caution when EC fluxes yield higher C sequestration than biomass (tree ring increments and inventory) based estimates. Nevertheless, the multitude of high time resolution data of *NEE* and *L.E* for such a long period has fostered our understanding of ecosystem functioning and can be applied to improve process-based models.

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