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Application of the ACASA model for a spruce forest and a nearby patchy clearing

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Abstract. The ACASA (Advanced Canopy-Atmosphere-Soil Algorithm) model, with a higher order closure for tall vegetation, has already been successfully tested and validated for spruce forests. The aim of this paper is the further application for a clearing with a heterogeneous structure of the underlying surface. The comparison with flux data shows a good agreement with a footprint aggregated tile approach of the model. However, the results of a comparison with a tile approach on the basis of the mean land use classification of the clearing is not significantly different. It is assumed that the footprint model is not accurate enough to separate small scale heterogeneities. All measured fluxes are corrected for energy balance closure with a Bowen ratio and a buoyancy flux correction method. The comparison with the model – where the energy balance is closed – shows that the buoyancy correction for Bowen ratios > 1.5 better fits the measured data. For lower Bowen ratios, the correction probably lies between both methods, but the amount of available data was too small to make a conclusion. With an assumption of a similarity between water and carbon dioxide fluxes, no correction of the net ecosystem exchange is necessary for Bowen ratios > 1.5.

1 Introduction

The comparison of modeled and measured energy and matter fluxes in a heterogeneous landscape is still a challenge. On the one hand, models must be applied for different surface types, while on the other hand the comparison of the fluxes is only possible on the basis of the flux footprints. Therefore, the modeled fluxes must be aggregated, e.g. with a tile approach (Mölders, 2012) based on the size of the flux footprint, which changes with the wind speed and the stratification. This method was described by Leclerc and Foken (2014).

A further problem is the so-called unclosed energy balance. The energy balance with turbulence measurements (eddy-covariance method, Aubinet et al., 2012) is not closed by an amount of up to 30 % (Foken, 2008), while the models close the energy balance by definition. The main reason for this is most likely the presence of fluxes caused by larger turbulence structures like secondary circulations (Foken, 2008). Measurement data must be corrected before comparison with model outputs can be made. The missing flux will be distributed between the sensible and the latent heat flux according to the Bowen ratio (Twine et al., 2000) or the buoyancy flux (Charuchittipan et al., 2014). Carbon and other trace gas fluxes have not been corrected before the present study.

Simulating the turbulent transfer for heterogeneous landscapes utilizing a one-dimensional SVAT model (Soil-Vegetation-Atmosphere Transfer) represents a multi-faceted challenge. For forest, coherent structures are a typical phenomenon of turbulent exchange (Gao et al., 1989; Bergström and Högström, 1989), and they can be measured with the eddy covariance technique. However, coherent structures modify the turbulent transfer of energy and matter in a manner that complicates capturing them with models. Higher order closure models are able to overcome this problem (Deardorff, 1966).

In this study the Advanced Canopy-Atmosphere-Soil Algorithm (ACASA, Pyles et al., 2000) has been utilized for the simulation of the turbulent transfer for a forest-clearing transition. Since a third order closure scheme is implemented in ACASA (Meyers and Paw U, 1986), a more exact resolution of the turbulent structure for forest is provided. Counter-gradient fluxes (Deardorff, 1966) are therefore resolved by the model and the amount of turbulent flux caused by coherent structures is considered. However, the influence of secondary structures on the energy balance cannot be taken into account by a one-dimensional model.

The ACASA model is much better suited to handling coherent structures and counter gradients than classical SVAT models with a first order closure (Staudt et al., 2011; Falge et al., 2017). The overall aim of this investigation is to analyze whether ACASA can simulate the fluxes over tall and low vegetation in an appropriate way. Additionally, it is evaluated whether the energy balance closure corrected flux measurements better fit the fluxes simulated by ACASA. Field measurements of the FLUXNET site 'Waldstein-Weidenbrunnen' (DE-Bay) were therefore complemented by additional measurements and have been simulated with ACASA for forest and clearing with respect to turbulent transfer. Furthermore, for the simulation of the clearing a tile approach is utilized to consider the different vegetation types for this area. We have accordingly specified plant parameters to model the different vegetation types, and the weighting of the plant individual simulations has been performed by two different methods: i) the mean plant distribution in the clearing, as well as ii) the footprint of different plant classes.

2 Material and methods

2.1 Waldstein-Weidenbrunnen site

The experimental data for the initialization of the model and the comparison of the results were collected during the third intensive observation period (IOP3) of the EGER (ExchanGE processes in mountainous Regions) project (Foken et al., 2012). The IOP3 campaign took place from 13 June to 26 July 2011. The EGER project mainly aimed at capturing the relevant exchange processes within the soil-vegetation-atmosphere framework and their interactions at different scales, and the work in IOP3 thereby focused on the role of surface heterogeneities in atmospheric exchange and chemistry as well as biogeochemistry.

The experimental site (50°8'N, 11°52'E, about 775 m a.s.l.) is part of the Bayreuth Centre of Ecological and Environmental

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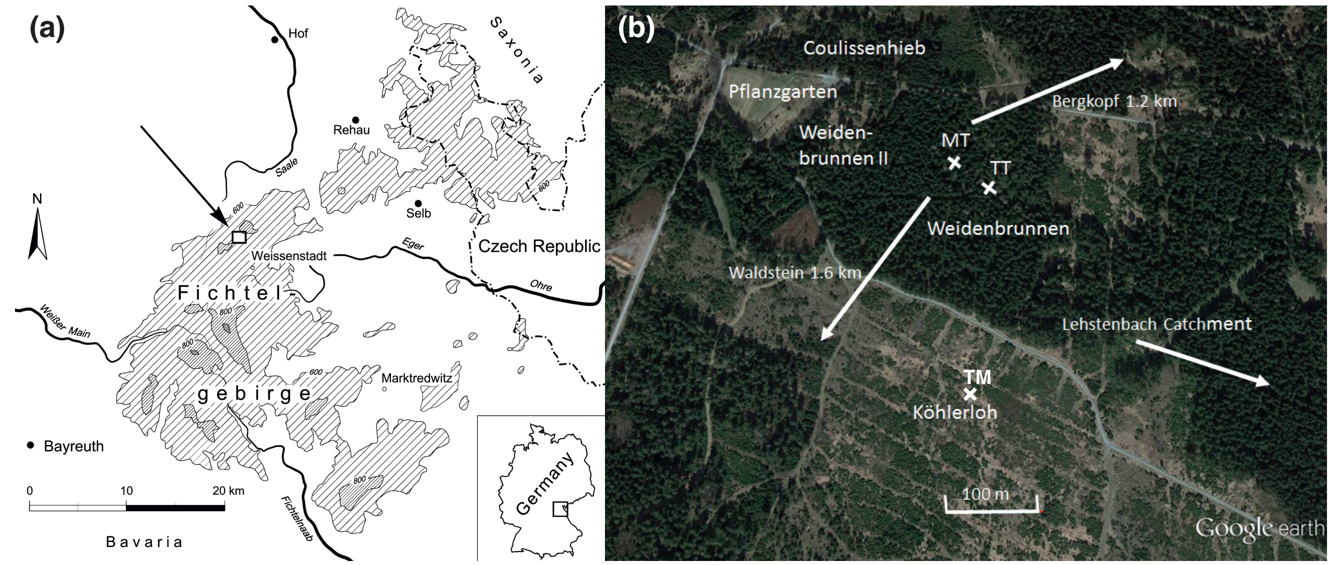

Figure 1. (a) Location of the BayCEER research site at the 'Waldstein' hillsides in the 'Fichtelgebirge' mountains (modified from Gerstberger et al. (2004)), published with kind permission of ©Springer, Berlin, Heidelberg 2004, All Rights Reserved; (b) Aerial picture of the patchy landscape showing meteorological towers/masts as well as the measuring points that are important for this study. MT: Main Tower, TT: Turbulence Tower, TM: Turbulence Mast (modified from Foken et al. (2017a), Published with kind permission of ©Springer, Berlin Heidelberg 2017 and ©Google earth, 2015, All Rights Reserved).

Research (BayCEER) and lies in the upper part of the 'Lehstenbach' catchment (Fig. 1a). It is situated between two hilltops: to the south-west the 'Großer Waldstein' (879 m a.s.l.) and the 'Bergkopf' (857 m a.s.l.) to the north-east. The Lehstenbach catchment is part of the slopes of the 'Waldstein' in the north-western part of the 'Fichtelgebirge' mountains. The 'Fichtelgebirge' is a low mountain range in north-eastern Bavaria, Germany and is mostly densely forested.

The measurements of IOP3 were carried out in a spruce forest next to the FLUXNET site 'Waldstein-Weidenbrunnen' (DE-Bay) and in a nearby clearing with heterogeneous low vegetation located to the south of the FLUXNET site (Fig. 1b). The clearing was created by a wind throw on January 18, 2007 that was induced by the European windstorm Kyrill (Foken et al., 2012). The vegetation of the measurement site is heterogeneous and there is a slope of 3 ° from the pine forest to the clearing (from north to south). A more detailed description of the surrounding topography is provided by Foken et al. (2017a).

The forest consists mainly of Norway spruce (*Picea abies*) with a stand height of about 27 m and a leaf area index (LAI) of 4.8 $m^2\,m^{-2}$ (Foken et al., 2017a). The stand age is circa 60 years (estimate from 2013) and the forest structure is characterized by an open trunk space as well as a dense crown space. The main foliage is located between 0.5 $z\,h_c^{-1}$ and 0.9 $z\,h_c^{-1}$, where z is the measurement height normalized by the stand height h_c. The understory comprises two-thirds crinkled hairgrass (*Deschampsia flexuosa*) and moss (together LAI of 0.5 $m^2\,m^{-2}$ and less) and one third characterized by blueberry (*Vaccinium myrtillus*) and young Norway spruce (*Picea abies*, together PAI of 3.5 $m^2\,m^{-2}$). The vegetation of the clearing is a conglomeration of young spruce trees, blueberry (*Vaccinium myrtillus*), and different grasses (e. g. *Calamagrostis, Agrostis, Poaceae*). However,

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Table 1. Vegetation at the Köhlerloh clearing with their main characteristics according to Foken et al. (2017a).

Species	**Ground cover in %**	**Height in m**	**PAI in $m^2\,m^{-2}$**
Crinkled hairgrass (*Deschampsia flexuosa*)	21.7	0.17 ± 0.05	2.65 ± 1.08
Young spruce (*Picea abies*)	21.4	1.21 ± 0.50	$8.67 \pm 2{,}29$
Blueberry (*Vaccinium myrtillus*)	15.9	0.27 ± 0.10	3.46 ± 1.05
Reed, bent, and true grasses (*Calamagrostis, Agrostis, Poaceae*)	9.0	0.42 ± 0.11	3.43 ± 1.07
Rush and sedge family (*Juncaceae, Cyperaceae*)	3.1	0.74 ± 0.13	1.77 ± 0.60
Other herbaceous*	1.6	/	/
Moss	0.9	/	/
Dead grass, bare soil	7.2	/	/
Dead wood	18.8	/	/
Small ditches	0.2	/	/

* This includes: *Digitalis purpurea* (common foxglove), *Epilobium angustifolium* (willow herb), and *Urtica dioica* (stinging nettle)

dead wood as well as bare soil are also elements of the clearing, and together they make up one third of the ground cover of this area. The clearing also contains approximately 2 % young deciduous trees: alder (*Alnus*), maple (*Acer*), beech (*Fagus*), and sorbus (*Sorbus*), with a greater canopy height than the remaining species. Due to the heterogeneous vegetation at the clearing, no distinct mean canopy height can be estimated for the clearing. Table 1 provides an overview of the species present and their mean canopy height.

2.2 Experimental setup and data

During IOP3, high-frequency turbulence measurements were conducted at different measurement towers (Fig. 1b). For this study, especially the data from the towers in the forest (MT, TT) and the turbulence mast at the clearing (TM) have been utilized. The towers and masts were generally equipped with 3D sonic anemometers, to enable collection of information about wind components (u, v, w) and the sonic temperature (T_S). In the majority of cases, high-frequency gas analyzers for carbon dioxide (c_{CO_2}) and water vapor (q) were installed in conjunction with sonic anemometers. This allowed the turbulent exchange for forest and clearing to be investigated with the devices as summarized in Table 2, and this has been utilized for comparison with simulations. Raw flux data (20 Hz) have been processed with the TK3 software (Mauder and Foken, 2015). The flux data have been additionally classified by their quality according to the classification scheme by Foken et al. (2004). For comparison with model results, only data with quality flags of 6 and better have been utilized. Furthermore, the flux measurements have been energy balance corrected with the methods described in Sect. 2.4.

The ACASA model needs half-hourly meteorological input values as well as mean values of soil temperature and soil moisture for initialization. These input values (see Table 2) are provided by standard measurements at the "Pflanzgarten" (Fig. 1b) and measurements at the Main Tower (MT) for the spruce forest as well as at the Turbulence Mast (TM) for the clearing. Table 2 provides an overview of the meteorological input data for the two simulated sites and the corresponding instrumentation.

Three Golden Day Periods (GDPs) were selected within IOP3 because of fair weather conditions and predominantly good performance of the measurement devices. The first GDP was from 26 to 29 June 2011 (corresponding to the 177 to 180 day of the year, DOY). On the last three days of this period, clear sky conditions prevailed until 2 p.m. as well as moderate westerly (26./ 27.) or easterly (28./ 29.) winds. The second GDP occurred from 4 to 8 July 2011 (DOY: 185 to 189), with the best weather conditions on 6 and 7 July and partly overcast sky on the rest of the days. The wind in this period was weak and blew from the west (4./7./8.) or east (5./6.). Minor amounts of precipitation were measured on 4 and 8 July. For the last GDP from 14 to 17 July 2011 (DOY: 195 to 198) data are missing for the clearing at 5.5 m.

2.3 The ACASA model

ACASA (Pyles et al., 2000) was utilized to simulate turbulent transfer of heat, water vapor, and CO_2 for spruce forest and clearing. ACASA is a multi-layer SVAT model developed at the University of California, Davis. The main feature of ACASA is that the turbulent transfer within and above the canopy is calculated by a diabatic, third-order closure method, which is based on the theoretical work of Meyers and Paw U (1986, 1987). The multi-layer structure of ACASA is represented by 20 evenly distributed atmospheric layers, which reach from trunk space to twice the canopy height, and by 15 soil layers. For the calculation of leaf, stem, and soil surface temperatures, the fourth-order polynomial scheme of Paw U and Gao (1988) is incorporated. This method allows the calculation of the temperatures of these components without also making substantial errors in the case of significant deviations from the ambient temperature.

Direct as well as diffuse radiation can be absorbed, transmitted, emitted or reflected by the canopy, whereby these processes are dependent on the leaf distribution of the plants. For this purpose, the vegetation is distributed in 10 different leaf angle classes (Meyers, 1985). In order to enable a preferably exact allocation of the incoming energy to sensible and latent heat fluxes, a leaf energy balance equation has to be solved. Plant physiological feedback to micro-environmental conditions is incorporated by approaches of Leuning (1990) and Collatz et al. (1991) to the Bell-Berry stomatal conductance combined with photosynthetic rates calculated after an equation of Farquhar and Caemmerer (1982), whereby coupling follows standards of Su and Paw U (1996). ACASA also includes canopy heat storage, which is mainly important for taller vegetation, and canopy interception of precipitation. For thermal and hydrological aspects the soil model utilizes diffusive approaches from a module that is incorporated in MAPS (Mesoscale Analysis and Prediction System). This component of the framework replaces a former description of the soil layer in ACASA and is described in more detail by Smirnova et al. (1997, 2000).

The ACASA model was adapted from a version of April 2013. The model was modified in three parts. The first change relates to the soil respiration calculations and was already examined by Staudt et al. (2010) for spruce. The original soil moisture attenuation factor was disabled because it not only reduced soil microbial respiration during dry periods, but also enhanced respiration rates to unreasonably high values during wet periods. This finding is consistent with investigations of Isaac et al. (2007). To overcome this issue, the temperature dependent respiration rate R_T is calculated by an Arrhenius type equation

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Table 2. Meteorological instrumentation for the determination of the sensible and the latent heat flux as well as the net ecosystem exchange (NEE) for forest and clearing at different measurement towers in distinct heights, using the eddy-covariance technique and the most important input parameter of the model (mean CO_2 concentration averaged from the turbulence data). Documentation of the complete data set is available in Foken (2017a).

Measurement site	**Parameter**	**Height**	**Device**
Pflanzgarten	Precipitation	1 m	OMC 212, Adolf Thies GmbH & Co. KG
	Pressure	2 m	Ammonit Gesellschaft für Messtechnik mbH
Weidenbrunnen,	Wind vector and sonic temperature (20 Hz)	32.5 m	USA-1, METEK GmbH
Main Tower (MT)	Humidity (20 Hz)	32 m	LI-7000†, LI-COR Biosciences
	CO_2 concentration (20 Hz)	32 m	LI-7000†, LI-COR Biosciences
	Temperature and relative humidity	31 m	Frankenberger ventilated psychrometer, Theodor Friedrichs & Co
	Wind velocity	31 m	Cup anemometer, Theodor Friedrichs & Co
	Downwelling shortwave radiation	29.5 m	CM 14, Kipp & Zonen
	Downwelling longwave radiation	29.5 m	CG 2, Kipp & Zonen
Weidenbrunnen,	CO_2 concentration (20 Hz)	36 m	LI-7500 §, LI-COR Biosciences
Turbulence Tower (TT)	Wind vector (20 Hz)	36 m	USA-1, METEK
Köhlerloh	Wind vector and sonic temperature (20 Hz)	2.25 m/5.5 m	CSAT3, Campbell Sci. Inc.
Turbulence Mast (TM)	Humidity (20 Hz)	2.25 m/5.5 m	LI-7000†/ LI-7500 §, LI-COR Biosciences*
	CO_2 concentration (20 Hz)	2.25 m/5.5 m	LI-7000†/ LI-7500 §, LI-COR Biosciences*
	Downwelling shortwave radiation	2.0 m	CNRN4 Kipp & Zonen
	Downwelling longwave radiation	2.0 m	CNRN4 Kipp & Zonen

* LI – 7000 in 2.25 m and LI – 7500 in 5.5 m.

† closed path gas analyzer, § open path gas analyzer.

(Hamilton et al., 2001):

$$R_{\mathrm{T}} = R_0 \cdot \exp\left[0.1 \cdot T_{\mathrm{s}} \cdot \ln\left(Q_{10}\right)\right]. \quad (1)$$

Here, R_0 means the basal respiration rate at 0 °C (μmol m^{-2} s^{-1}) based on the surface area of the roots or microbes, T_{s} the current soil temperature (K), and Q_{10} the temperature factor for 10 °C temperature increase. The soil respiration is separately calculated for roots and microbes according to Eq. (1), and afterwards summed to yield the total soil respiration (Staudt et al., 2010). The modifications for the soil respiration explained for spruce have been also adapted for the clearing, in order to have the same model setup for both surfaces. Moreover, the NEE fluxes at the clearing are too small to allow crucial changes due to this modified soil respiration to be apparent, but it can be assumed that the original setup might lead to smaller intercepts in the regression analysis shown in Sect. 3.2.2.

The second change according to Staudt et al. (2010) was made to the calculation of photosynthesis. Originally, in the plant physiology sub-module, the temperature dependence of the maximum catalytic activity of Rubisco at saturated ribulose biphosphate (RuBP) and saturated CO_2, V_{cmax} (μmol m^{-2} s^{-1}), is described by a third-order polynomial proposed by Kirschbaum and Farquhar (1984). This function was deduced from measurements in the temperature range of 15 to 32 °C. A drawback of the polynomial is the unrealistic increase of V_{cmax} for temperatures below 10 °C, which was already noticed by Leuning (1997). At our site, temperatures less than 10 °C are very common and, therefore, the relation was replaced by the temperature dependence of V_{cmax} utilized in the leaf sub-module PSN6 of the model SVAT-CN (Falge et al., 1996, 2005; Medlyn et al., 2002):

$$V_{cmax} = V_{cmax25} \frac{exp\left[\frac{\Delta H_{\mathrm{a}}\cdot(T_{\mathrm{L}}-T_{\mathrm{r}ef})}{R\cdot T_{\mathrm{L}}\cdot T_{\mathrm{r}ef}}\right]\cdot\left\{1+exp\left[\frac{\Delta S\cdot T_{\mathrm{r}ef}-\Delta H_{\mathrm{d}}}{R\cdot T_{\mathrm{r}ef}}\right]\right\}}{1+exp\left[\frac{\Delta S\cdot T_{\mathrm{L}}-\Delta H_{\mathrm{d}}}{R\cdot T_{\mathrm{L}}}\right]}. \quad (2)$$

Here, T_{L} (K) is the leaf temperature, V_{cmax25} is the maximum carboxylation rate at the reference temperature $T_{\mathrm{r}ef}$ (298.15 K), and R is the universal gas constant (8.31 J mol^{-1} K^{-1}), ΔS is an entropy term, and ΔH_{a} and ΔH_{d} are the activation and the deactivation energy, respectively. The parameter set utilized for the clearing is shown in Table 3. The parameter set for the forest is provided by Staudt et al. (2010).

The third adjustment relates to the day respiration for leaves. For a long time, the day respiratory metabolism of plants presented one of the major conundrums of plant metabolism (Heskel et al., 2013). Tcherkez et al. (2008) quantified the day respiration as about one half of the night respiration rate. For this study that relation was implemented in the ACASA model. Therefore, the leaf respiration is multiplied by a factor of 0.5 if the photosynthetically active radiation (PAR) exceeds 0 W m^{-2}.

2.4 Energy balance correction

The eddy-covariance data of sensible heat, latent heat, and carbon dioxide flux have been energy balance corrected for the comparison with the simulations.

For the correction of the energy fluxes, the residual (Res) arises from the following assumption:

$$\mathrm{Res} = Q_{\mathrm{S}} - H - LE - G - \Delta S, \quad (3)$$

where, Q_{S} denotes net radiation, H sensible heat flux, LE latent heat flux, and ΔS the heat storage term of the plant canopy, which was determined according to the investigations of Haverd et al. (2007) and Lindroth et al. (2010). Here, the heat storage term was only estimated for the spruce forest because of its larger biomass compared to the vegetation in the clearing. The heat storage was calculated with the following relation (Lindroth et al., 2010; Haverd et al., 2007):

$$\Delta S = m_{\mathrm{f}} c_{\mathrm{f}} \frac{(T_{\mathrm{a}}(t) - T_{\mathrm{a}}(t-\Delta t))}{\Delta t}, \quad (4)$$

with m_{f} the biomass of the forest, c_{f} the specific heat capacity of wood (c_{f} = 1702.8 J kg^{-1} K^{-1}), and T_{a} the air temperature in the spruce canopy. In this study, two different methods for energy balance correction have been applied to the measurements of

Table 3. Plant morphological parameter settings of the ACASA model utilized for the clearing simulations according to Falge et al. (2017).

Parameter	**Dimension**	*Vaccinium*	*Deschampsia*	*Calamagrostis*	*Juncus*	*Picea abies*
Maximum rate of carboxylation at 25 °C †	μmol m^{-2} s^{-1}	26.61	29.53	45.57	30.39	31.78
Activation energy ΔH_a †	J mol^{-1}	46986	34030	37211	41226	29487
Deactivation energy ΔH_d †	J mol^{-1}	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$
Entropy †	J mol^{-1} K^{-1}	238.8	254.4	243.2	240.1	245.0
Activation energy for RuBP regeneration §	J mol^{-1}	52,642	48,000	137,205	16,745	36,185
Entropy term for RuBP regeneration §	J mol^{-1}	488.2	511.4	468.7	492.4	486.2
Deactivation energy for RuBP regenerationn §	J mol^{-1}	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$	$2{\cdot}10^5$
Potential rate of electron transport ati 25 °C	μmol m^{-2} s^{-1}	86.12	157.46	198.32	128.92	123.98
Slope of Ball – Berry formula	/	10.09	10.58	10.68	8.17	9.40
Minimal stomata conductance	mol m^{-2} s^{-1}	0.050	0.127	0.049	0.002	0.054
O_2 concentration within the cells	mmol mol^{-1}	0.21	0.21	0.21	0.21	0.21
Quantum efficiency	/	0.0626	0.1223	0.0809	0.1215	0.0851
Leaf respiration rate at 0°C	μmol m^{-2} s^{-1}	0.1154	0.9174	0.0817	0.6815	0.5413
Q_{10} temperature coefficient for leaves	/	2.7316	1.4226	2.7167	1.4632	1.8653
Mean leaf diameter	m	0.013	0.0004	0.005	0.005	0.001
Contribution to Köhlerloh clearing *	%	17.5	21.7	9.0	3.1	21.4

† To calculate maximum rate of carboxylation at 25 °C

§ Ribulose-1,5-biphosphate

* furthermore 27.3 % dead wood

IOP3. The first correction method is introduced by Twine et al. (2000) and preserves the Bowen ratio. This method is usually utilized for the correction of heat fluxes under the assumption of measuring errors, but requires their scalar similarity. Henceforth, this method is abbreviated with EBC-Bo. The second correction method accounts for near surface secondary circulations, which transport more sensible heat. Therefore, the alternative correction method (EBC-HB) proposed by Charuchittipan et al. (2014) utilizes the buoyancy flux ratio. Here, for the typical range of the Bowen ratio, more residual energy is ascribed to the sensible heat flux, as was done in several studies (Foken et al., 2011). The difference to the EBC-Bo correction is especially pronounced for low Bowen ratios. At night, the applicability of the corrections is limited due to the occurrence of minor or negative heat fluxes.

The discrepancy between measured and simulated NEE can be an effect of the unclosed energy balance on the CO_2 fluxes. Therefore, we propose a new correction method on the basis of the good scalar similarity between the humidity and the carbon dioxide concentration (Ruppert et al., 2006). The measured NEE is corrected by referring to the energy balance corrected latent heat flux, which is introduced in (Falge et al., 2017). For this purpose, the ratio k between the corrected and the uncorrected latent heat fluxes is calculated for both correction methods:

$$k_{\mathrm{Bo}} = \frac{LE_{\mathrm{Bo}}}{LE} \quad \text{and} \quad k_{\mathrm{HB}} = \frac{LE_{\mathrm{HB}}}{LE}\,. \tag{5}$$

The measured NEE value was then multiplied with the respective correction factor k_{Bo} or k_{HB}. This correction method is proposed for the NEE for the first time and the applicability of this approach is therefore evaluated.

2.5 Footprint model

Nowadays, footprint models are a commonly used tool for the identification of the source area of flux measurements (Leclerc and Foken, 2014). For the footprint calculations of this study, a Lagrangian footprint model is applied (Rannik et al., 2000, 2003; Göckede et al., 2006), whereby a spectral method of the flux averaging of surface characteristics (roughness length) according to Hasager and Jensen (1999) is employed. The sensitivity of the Lagrangian footprint model to the turbulence statistics was tested by Göckede et al. (2007) for the Waldstein-Weidenbrunnen site. A footprint climatology and footprint studies, including the effect of the footprint on the data quality, are available from Foken et al. (2017b). On average, more than 80 % of the target area is forest. Only for southerly winds and stable stratification does the Köhlerloh clearing have a significant influence on the fluxes measured at the Main Tower MT.

In a study by Reithmaier et al. (2006) the land use for the Waldstein-Weidenbrunnen site was determined and mapped, and this was tested for footprint applications. Due to the distinct small-scale heterogeneities, the land cover map applied here has a high resolution ($4.5 \times 4.5\,\mathrm{m}^2$). This grid size is in agreement with the size of the typical heterogeneities and the recommendations for footprint analyses for low measuring heights (Leclerc and Foken, 2014). The calculated footprints have been used to generate tile approaches of the model.

2.6 Comparison of measured and modeled fluxes

Measured and modeled fluxes for the forest as well as the Köhlerloh clearing have been energy balance corrected and compared for the first time by Falge et al. (2017). This overview paper about modeling efforts at the Waldstein-Weidenbrunnen site did not allow very detailed investigations – mainly of area averaging of fluxes and energy balance closure – thus, this study is an updated investigation. However, it has been found that the energy balance closure for the sensible heat, the latent heat, and the NEE was better for the buoyancy flux correction, but the results are partly inconclusive. Therefore, the simple comparison of a modeled tile approach for the Köhlerloh clearing with the eddy-covariance measurements of the Turbulence Mast TM was replaced by a footprint weighted tile approach for single measurements following Biermann et al. (2014). This means that the measured flux has been compared with a modeled tile approach, where model simulations for the different land use types have been weighted according to their contribution to the footprint. The comparisons have been made mainly for the first and the second Golden Day Periods because of missing data from the clearing in the third Golden Day Period. For the forest site all data have been included in the energy balance correction analysis.

3 Results and discussion

3.1 Footprint climatology for the Köhlerloh clearing

The footprint climatology of the of the mainly forested Waldstein-Weidenbrunnen site is well described in many publications like Göckede et al. (2008) and summarized by Foken et al. (2017b). In the following, the footprint climatology of the clearing site Köhlerloh (Turbulence mast TM) is analyzed. Only for southerly winds and stable stratification does the Köhlerloh clearing have a significant influence on the fluxes measured at the Main Tower (MT). Therefore, only the footprint of the Köhlerloh site (Turbulence mast TM) is analyzed in the following.

As an overview, the footprint climatology for the period from June, 26 to July, 17 2011 has been calculated, and is a superposition of all individual footprints. Fig. 2 shows the footprint climatology for the Turbulence Mast TM in two different heights at the clearing. The main difference in the footprint climatology between the different stratification appears for stable conditions in both measuring heights. Thus, for unstable and neutral stratification, mainly the clearing contributes to the turbulent fluxes at the Turbulence Mast TM. For stable stratification and northerly wind directions, the spruce forest has additional influence on the measured turbulent flux at TM (see Fig. 2). For 5.5 m measuring height, the footprint source areas are generally enhanced/extended. For the stable stratified case and 2.25 m measuring height, only the north-easterly part of the spruce forest is included in the outer source region of the turbulent flux. For stable cases in 5.5 m measuring height, a stronger influence from the north-easterly region of the spruce forest as well as slight influence from the north-westerly spruce areas connected to the forest edge is calculated. The slight differences in the shape of the footprint areas between the two measuring heights might be caused by data gaps for both measuring heights, which exist at different time periods.

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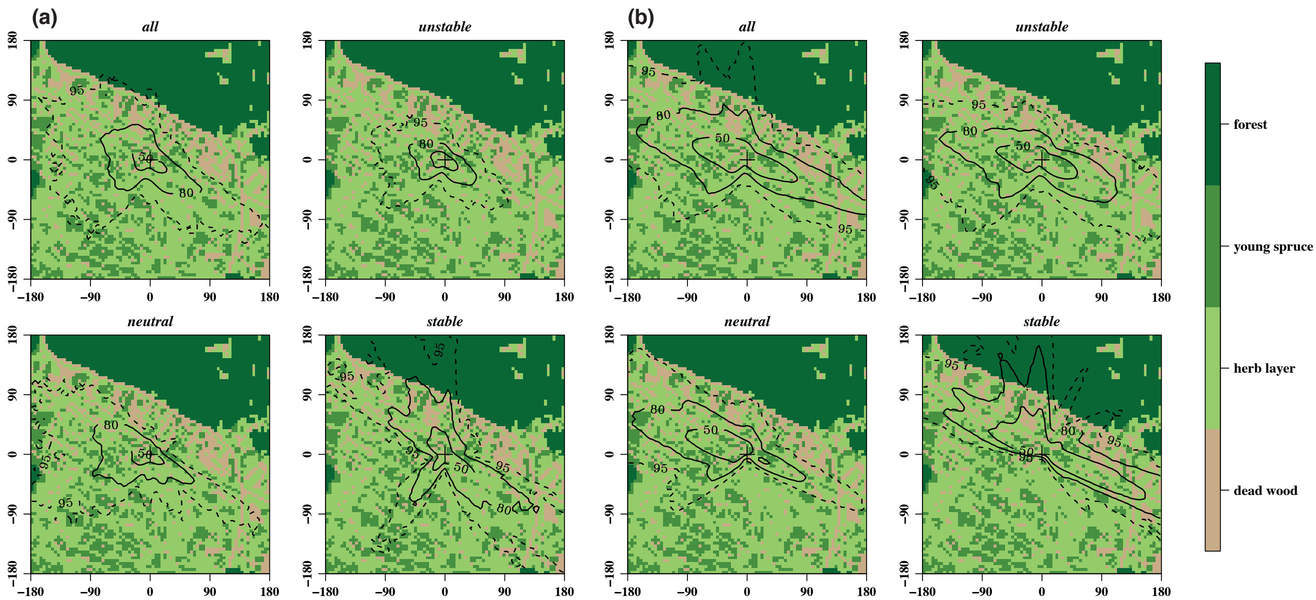

Figure 2. Footprint climatology of the Köhlerloh clearing (26.06. to 17.07.2011) at the Turbulence Mast TM for the three stability classes; a) At 2.25 measuring height; b) At 5.5 measuring height. Here, four different land-use classes are considered, with the herb layer being composed of *Deschampsia*, *Calamagrostis*, *Juncus*, and *Vaccinium*.

3.2 Comparison of modeled and measured fluxes

3.2.1 Daily cycles

Falge et al. (2017) have already compared the sensible and the latent heat flux as well as the NEE for the forest (MT) and the clearing (TM, 2.25 m). They found that the sensible heat flux corrected with the buoyancy flux agrees better with the modeled data than the flux corrected with the Bowen ratio for the first Golden Day Period. The result for the latent heat flux is similar and the NEE shows no significant differences. The NEE over the clearing was only about 50 % of the value over the forest.

In the following, we compare for the clearing the measured as well as the energy balance corrected fluxes, with the tile approach of the model according to i) the relevant footprint near the measurement point and ii) the land use distribution of the whole clearing. It was found that for the footprint of 2.25 m height there are no significant differences between either modeling approach due to the small size of the footprint (not shown). The results for TM with the footprint for 5.5 m measuring height are shown in Fig. 3 for the first and in Fig. 4 for the second Golden Day Period. The difference between both model approaches is more dominant in the first period, which had a Bowen ratio $Bo \geq 1$, while in the second period the Bowen ratio was often below 1. The difference in the land use characteristics were more dominant under drier conditions.

From the visual comparison of Figs. 3 and 4 it has been found that the buoyancy corrected sensible and latent heat fluxes obviously better agree with the model than do the Bowen ratio corrected fluxes. The scatter is too large to allow any trend for

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the NEE to be seen. There is also no clear finding as to whether the footprint weighted tile approach of the model (non-weighted approach not shown) gives better results. Obviously, the integrated fluxes of the tile approaches for the whole clearing and the footprint of the turbulence mast for 5.5 m height do not differ significantly. Probably not only the land use characteristics, but also the soil water content have a significant influence. This can be seen by the high measured latent heat fluxes in the first Golden Day Period (see Fig. 3). Further regression analyses are discussed in the following section for both weighting methods.

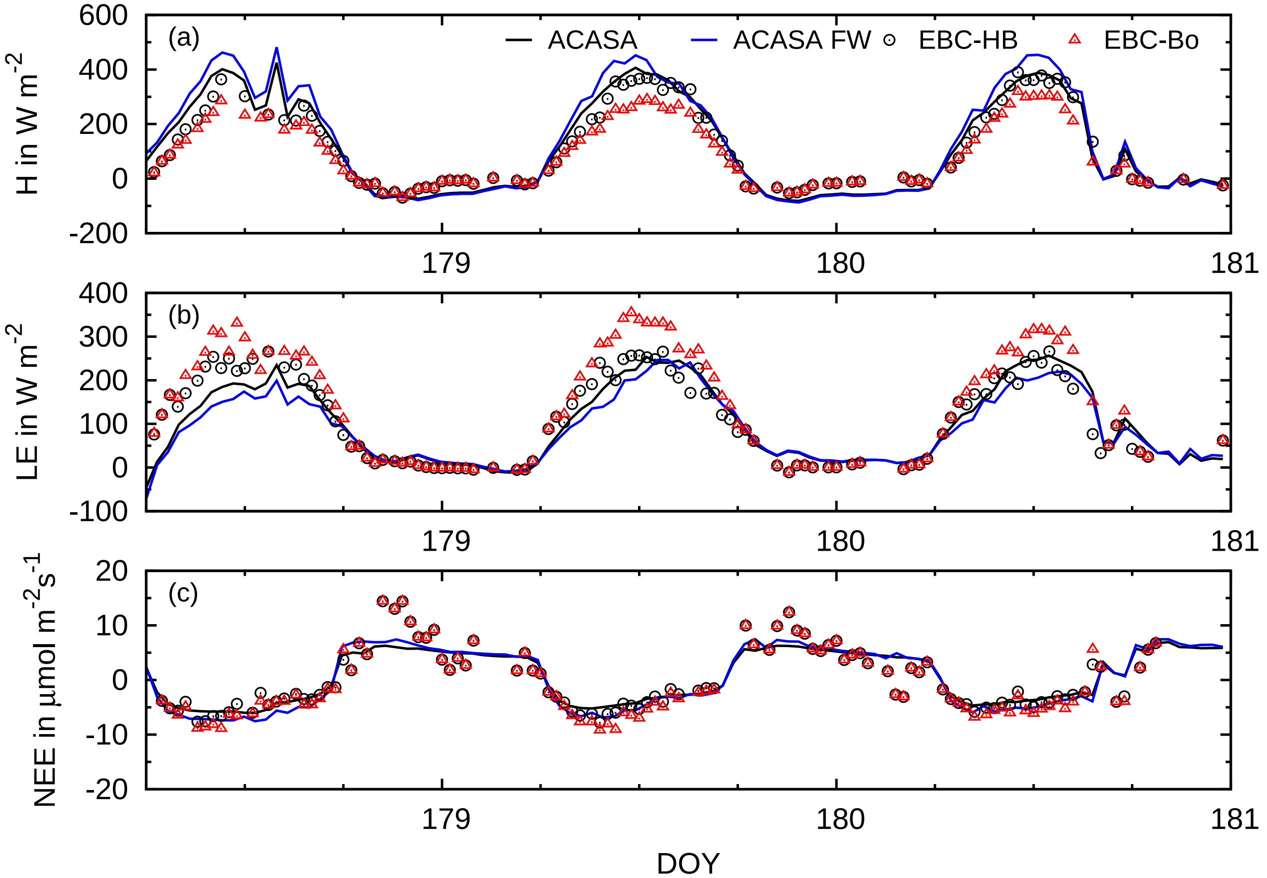

Figure 3. Comparison of ACASA model simulations with measured turbulent fluxes at TM (in 5.5 m measurement height) for the first GDP; a) Sensible heat (H); b) Latent heat (LE) and c) net ecosystem exchange (NEE). The black solid line displays ACASA simulations weighted by the mean plant distribution of the whole clearing and the blue solid line indicates ACASA simulations weighted by different plant classes within the footprint of the flux measurements. Energy balance corrected flux measurements are shown by black circles for the correction utilizing the buoyancy flux ratio (EBC-HB) and red triangles for correction with the Bowen ratio (EBC-Bo).

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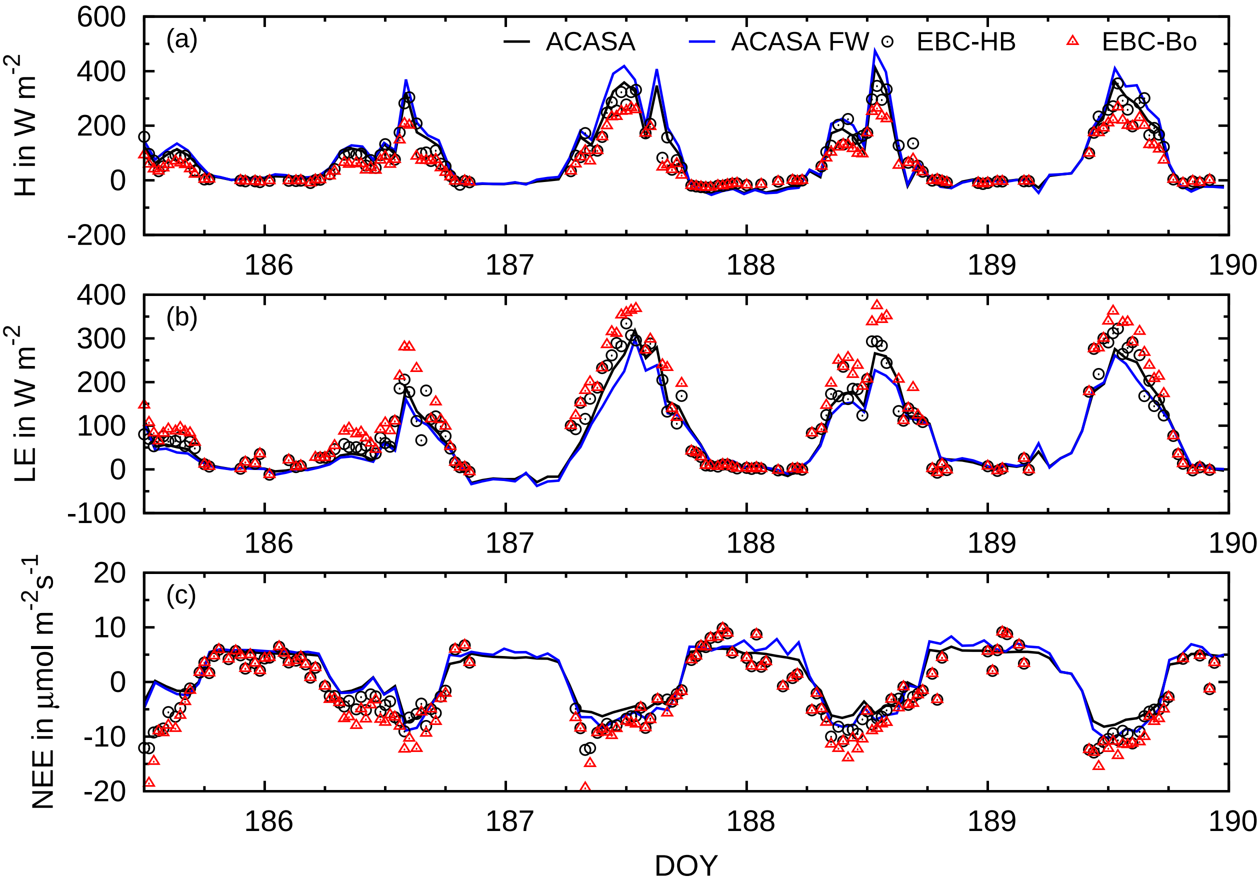

Figure 4. Comparison of ACASA model simulations with measured turbulent fluxes at TM (in 5.5 m measurement height) for the second GDP; a) Sensible heat (H); b) Latent heat (LE) and c) net ecosystem exchange (NEE). The black solid line displays ACASA simulations weighted by the mean plant distribution of the whole clearing and the blue solid line indicates ACASA simulations weighted by different plant classes within the footprint of the flux measurements. Energy balance corrected flux measurements are shown by black circles for the correction utilizing the buoyancy flux ratio (EBC-HB) and red triangles for correction with the Bowen ratio (EBC-Bo).

3.2.2 Regression analyses

Neither of the modeled nor the measured fluxes are free of errors and could be used as an independent parameter. Therefore, the errors are assumed to be similar and an orthogonal regression analysis for evenly distributed errors has been applied (Dunn, 2004). The regression has been achieved for the first two Golden Day Periods for the forest and the clearing (with and without footprint weighted tile approach). The regression analysis is calculated for the sensible (H) and the latent (LE) heat flux as well

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as the net ecosystem exchange (NEE). Furthermore, the available energy (AE), as the difference between net radiation and the ground heat flux as well as the heat storage in the biomass (the latter is only determined for forest), is shown. The results are given in Tables 4 and 5 as well as being partly illustrated in Fig. 5. Due to a non-equal distribution of the data points, the data have been binned for flux classes of the modeled data, whereby the number of bins have been chosen so that the measured flux data is equally distributed. Therefore, the observed trend in the data have not been artificially shifted due to the applied binning and further, the excluded data (for cases with $Bo < 0$ and too small nighttime fluxes) have merely been located in one bin. Fig. 5 is created without the confidence intervals for the regression curves because the fluxes only marginally scatter around the average regression curve and for the sake of improved clarity. Tables 4 and 5 additionally contain the results for the regressions through the point of origin because of the large intercepts observed in regression analysis. Nevertheless, the slope did not vary substantially between both regression methods.

The analysis of the eddy-covariance data show that in all cases, except for the latent heat in the second Golden Day Period, the fluxes are underestimated and an energy balance correction is necessary to obtain an agreement with the modeled data. All results are very similar for both Golden Day periods. For a discussion of the results included in Fig. 5 as well as Tables 4 and 5, the available energy is also shown and the therein considered fluxes are summarized. The net radiation is underestimated by the model by about 5 – 7 % for both sites (not shown). The ground heat flux and the storage in the biomass both amount to less than 10 % of the net radiation, with a large scatter between the measured and the modeled data. A significant difference from the 1:1 relationship has only been found for the ground heat flux of the clearing, which is higher by a factor of 2 for the experimental data. Due to the installation of the sensors the ground was probably less covered with vegetation, and thus could store more energy. For the forest site, the underestimation of the available energy by the model was only about 4 %. For the clearing site, the modeled available energy has a constant offset of 30 W m^{-2} and was therefore higher than the experimental data.

The effect of the different energy balance corrections is not equal for both sites. For the forest site, both corrections of the sensible heat flux agree quite well with the model, with slightly better values for the buoyancy correction. For the latent heat flux of the forest site, the measurements corrected according to the Bowen ratio are in better agreement with the simulations. Due to $Bo > 1$, the buoyancy correction overestimates the effect of thermal convection on the energy balance closure and the true correction might lie between both correction methods. The turbulent fluxes might be slightly higher than the modeled fluxes because of the measured available energy being about 4 % higher, as can be seen after applying both corrections (see also Sect. 3.2.3).

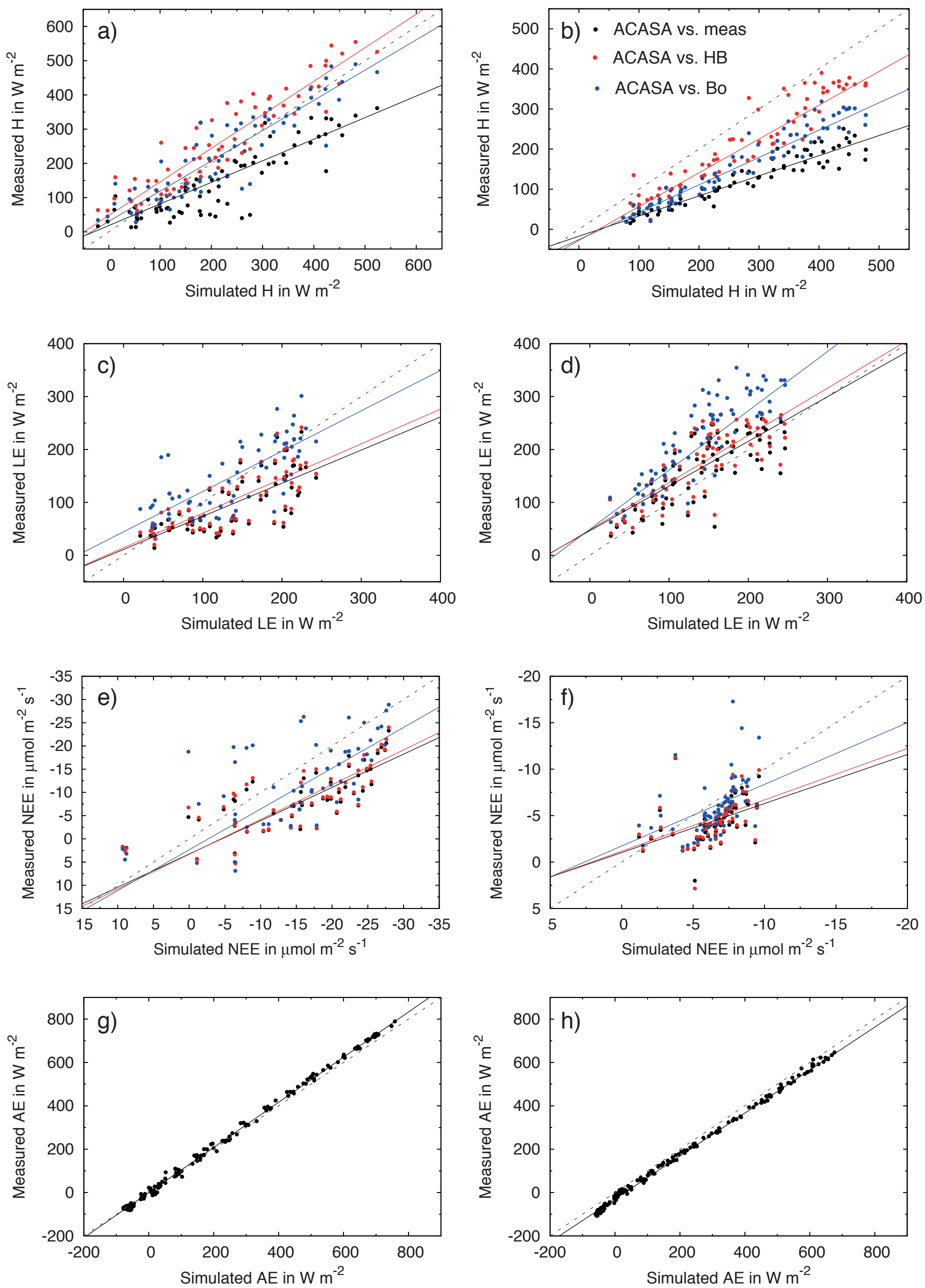

Figure 5. Example of the regression analysis of the measured and the simulated (ACASA) data for GDP 1 for a) and b) the sensible heat flux (H); c) and d) the latent heat flux (LE); e) and f) the net ecosystem exchange (NEE); and g) and h) the available energy (AE) above the forest (a, c, e, g) and above the clearing at 5.5 m height (footprint weighted modeled fluxes; b, d, f, h) for uncorrected (black), Bowen ratio corrected (blue), and buoyancy corrected (red) eddy-covariance data. The regression lines are based on binned data for 50 W m^{-2} or 2/4 μmol m^{-2} s^{-1} classes of the modeled data and an orthogonal regression. The analysis has been achieved for the first and second Golden Day Periods, with Tables 4 and 5 displaying the results of an orthogonal regression with as well as without assuming a zero intercept for the clearing and the forest, respectively.

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Table 4. Results of the comparison of the measured and the modeled flux data for different correction methods with an orthogonal regression for binned data points for the clearing with and without footprint weighting (for details see Fig.5, absolute values in W m^{-2} or μmol m^{-2} s^{-1} for the NEE).

Flux correction	First Golden Day Period, June 26-28 Slope	Absolute value	Slope zero intercept§	Corr. coeff.	Data bins	Second Golden Day Period, July 4-8 Slope	Absolute value	Slope zero intercept§	Corr. coeff.	Data bins
Sensible heat flux, clearing 5.5 m, footprint weighted tile approach										
No	0.50	-17.3	0.45	0.99	9	0.52	-15.8	0.46	0.98	9
Buoyancy	0.84	-27.9	0.76	0.99	9	0.72	9.3	0.75	0.99	9
Bowen	0.68	-25.7	0.61	1.00	9	0.61	-8.0	0.59	0.99	9
Sensible heat flux, clearing 5.5 m, non-footprint weighted tile approach										
no	0.61	-25.4	0.51	1.00	7	0.59	-22.7	0.51	0.98	8
buoyancy	1.01	-34.9	0.77	0.99	7	0.84	8.3	0.87	1.00	8
Bowen	0.83	-36.1	0.70	1.00	7	0.71	-11.7	0.67	0.99	8
Latent heat flux, clearing 5.5 m, footprint weighted tile approach										
No	0.84	46.4	1.14	0.98	5	1.02	13.7	1.09	0.98	6
Buoyancy	0.89	48.1	1.20	0.98	5	1.05	20.4	1.16	0.99	6
Bowen	1.20	49.1	1.51	1.00	5	1.25	36.5	1.44	0.99	6
Latent heat flux, clearing 5.5 m, non-footprint weighted tile approach										
no	0.84	36.4	1.07	0.97	6	1.03	-5.3	1.00	0.98	6
buoyancy	0.92	34.0	1.14	0.97	6	1.05	1.8	1.06	0.98	6
Bowen	1.19	39.2	1.43	0.99	6	1.16	29.5	1.31	0.99	6
NEE, clearing 5.5 m, footprint weighted tile approach										
No	0.53	-1.0	0.69	0.88	5	0.52	-2.3	0.84	0.94	7
Buoyancy	0.55	-1.2	0.74	0.87	5	0.55	-2.6	0.90	0.94	7
Bowen	0.66	-1.7	0.94	0.86	5	0.66	-3.9	1.20	0.94	7
NEE, clearing 5.5 m, non-footprint weighted tile approach										
no	0.64	-1.9	1.04	0.98	5	0.74	-3.0	1.25	0.98	6
buoyancy	0.62	-2.1	1.08	0.98	5	0.76	-3.3	1.33	0.98	6
Bowen	0.55	-3.1	1.25	0.97	5	0.89	-4.7	1.71	0.97	6
AE, clearing 5.5 m, footprint weighted tile approach										
Uniform†	0.99	-30.0	0.93	1.00	16	0.97	-18.2	0.93	1.00	15
AE†, clearing 5.5 m, non-footprint weighted tile approach										
uniform	1.04	-31.3	0.97	0.97	15	1.05	-23.7	1.00	1.00	15

§ Orthogonal regression considering a zero intercept; † AE is the same for all 3 methods because the heat storage term of the canopy and the ground heat flux are uniformly estimated

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Table 5. Results of the comparison of the measured and the modeled flux data for different correction methods with an orthogonal regression for binned data points for the forest (absolute values in W m^{-2} or μmol m^{-2} s^{-1} for the NEE).

Flux correction	First Golden Day Period, June 26-28					Second Golden Day Period, July 4-8				
	Slope	Absolute value	Slope zero intercept§	Corr. coeff.	Data bins	Slope	Absolute value	Slope zero intercept§	Corr. coeff.	Data bins
Sensible heat flux, forest 32 m										
No	0.63	18.4	0.69	0.98	11	0.69	-25.7	0.61	0.95	10
Buoyancy	0.98	47.8	1.13	0.99	11	0.91	25.6	0.99	0.99	10
Bowen	0.88	30.6	0.98	0.99	11	0.82	0.6	0.82	0.98	10
Latent heat flux, forest 32 m										
No	0.63	11.0	0.69	0.95	5	0.67	23.8	0.79	0.99	6
Buoyancy	0.65	14.2	0.74	0.94	5	0.69	33.2	0.86	0.99	6
Bowen	0.76	44.4	1.04	0.91	5	0.82	58.5	1.12	0.99	6
NEE, forest 32 m										
No	0.72	3.3	0.55	0.93	6	0.65	-1.1	0.70	0.96	8
Buoyancy	0.75	3.3	0.58	0.93	6	0.64	-2.4	0.76	0.95	8
Bowen	0.88	2.4	0.76	0.95	6	0.70	-7.3	1.06	0.81	8
AE, forest 32 m										
Uniform†	1.04	-0.2	1.04	1.00	17	1.05	-11.5	1.03	1.00	17

§ Orthogonal regression considering a zero intercept; † AE is the same for all 3 methods because the heat storage term of the canopy and the ground heat flux are uniformly estimated

However, for the clearing with $Bo < 1$, different results have been found: with the Bowen ratio correction, the sensible heat flux is significantly underestimated by about 30 % and the latent heat flux is overestimated by about 12 %. The buoyancy correction underestimates both fluxes by about 10 %. The measured latent heat flux is often larger than the modeled latent heat flux. This is probably a large effect of the plants in the footprint and the soil water content, which is not proportional to the land cover fraction used by the footprint model. Taking into account the 30 W m^{-2} higher available energy of the model, which is in the order of about 10 – 20 % of the turbulent fluxes (therefore, the modeled fluxes are higher by this value), the buoyancy correction is more appropriate for the clearing.

The correction of the NEE data seems to be necessary, but the underestimation by the model is still given. This could also be an overestimation by the measured fluxes due to the turbulence and the forest structure, discussed by Foken (2017b). Therefore, the Bowen ratio correction of the NEE for the forest seems to agree better, while over the clearing the fluxes are too small to allow useful conclusions to be made.

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3.2.3 Analysis of the energy balance closure correction

According to the findings in Sect. 3.2.2 that a large contribution of the unclosed energy balance is a missing sensible heat flux, we used the modeled data, which close the energy balance by definition – as an etalon, for the validation of the correction methods. Therefore, the modeled Bowen ratio was assumed to be true and the measured fluxes have been corrected in such a way that the energy balance was closed and the Bowen ratio agreed with the modeled Bowen ratio. Finally, the fraction of the residual attributed to the sensible heat flux has been determined and is shown in Fig. 6. Sometimes, when the measured latent heat flux was significantly larger than the modeled flux, the fraction was up to 150 %. This analysis was only made for the forest with a more homogeneous footprint. Fig. 6 also shows, for comparison, the proposed corrections according to the Bowen ratio (Twine et al., 2000) and the buoyancy flux (Charuchittipan et al., 2014). Obviously, the assumption that convection is responsible for the energy balance problem and that a large part of the residual should be added to the sensible heat flux, may be only true for $Bo > 1.5$. For lower Bowen ratios, the real correction might lie between both methods, and for $Bo < 1$ be more in accordance with the Bowen ratio correction. Unfortunately, the number of the available data points for $Bo < 1.5$ is very low, so that the presented results can only be interpreted as a tendency. This means that secondary circulations, probably responsible for the unclosed energy balance, are not only generated by convective processes. Additionally, this indicates that the Bowen-ratio correction is not a method that is applicable for the correction of the measurement errors that occur. Further research is necessary with other well parametrized models that close the energy balance very well, and data sets for lower Bowen ratios. Due to the assumption of a similarity between the water and carbon dioxide fluxes (Ruppert et al., 2006), neither the NEE flux nor the latent heat flux were corrected for high Bowen ratios. In conclusion, for spruce forests with typically high Bowen ratios, no correction of the NEE is necessary.

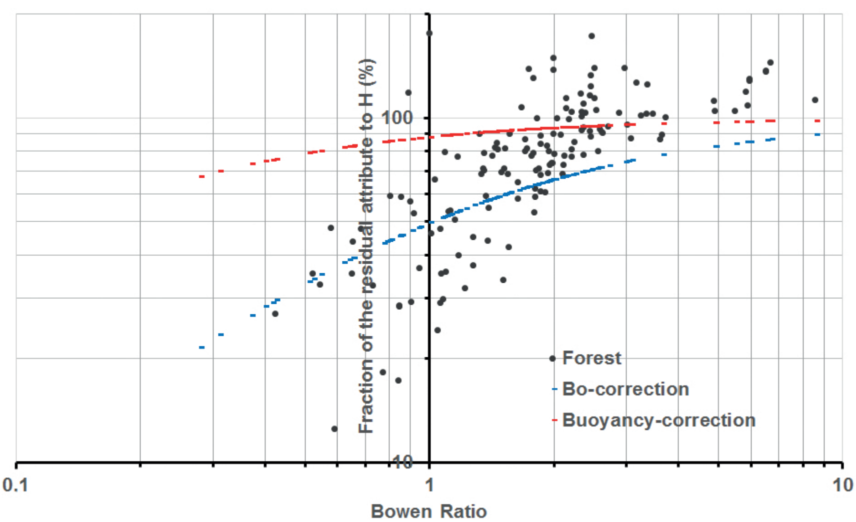

Figure 6. Fraction of the residual attributed to the sensible heat flux for the forest site (GDP 1, 2, and 3), under the assumption that the model calculated the true Bowen ratio, and according to the correction methods with the Bowen ratio (Twine et al., 2000) and the buoyancy flux (Charuchittipan et al., 2014).

3.2.4 Tile approach for a mixed forest site

The comparison of the modeled and the measured (ground truth) fluxes has shown that the ACASA model determines the fluxes for high and low vegetation with high accuracy, within the typical measurement uncertainty (Mauder et al., 2006, 2013) of eddy-covariance measurements, if the measured data are corrected for energy balance closure. Due to high Bowen ratios and large underestimation by the model, the buoyancy corrected fluxes show better results in comparison with the model. This offers the possibility of modeling fluxes over larger heterogeneous areas, like a catchment, with a tile approach. Even when the fluxes above the different land use types are significantly different and are changing, e.g. with the Bowen ratio, the tile approach achieves appropriate results. To illustrate these differences, Fig. 7 shows mean daily cycles for the Waldstein-Weidenbrunnen forest site and the heterogeneous Köhlerloh clearing, whereby every surface contributes 50 % to the weighted flux. The magnitudes of the sensible heat flux are, in general, higher at the forest than at the clearing. In contrast, during the day latent heat flux is higher for the forest and during night the dewfall is higher for the clearing. The main differences for both surfaces occur for the NEE. The magnitude of the NEE for the forest is sometimes more than twice of that from the clearing during the day. During the night, the differences between the NEE for the forest and the clearing are smaller. Falge et al. (2017)

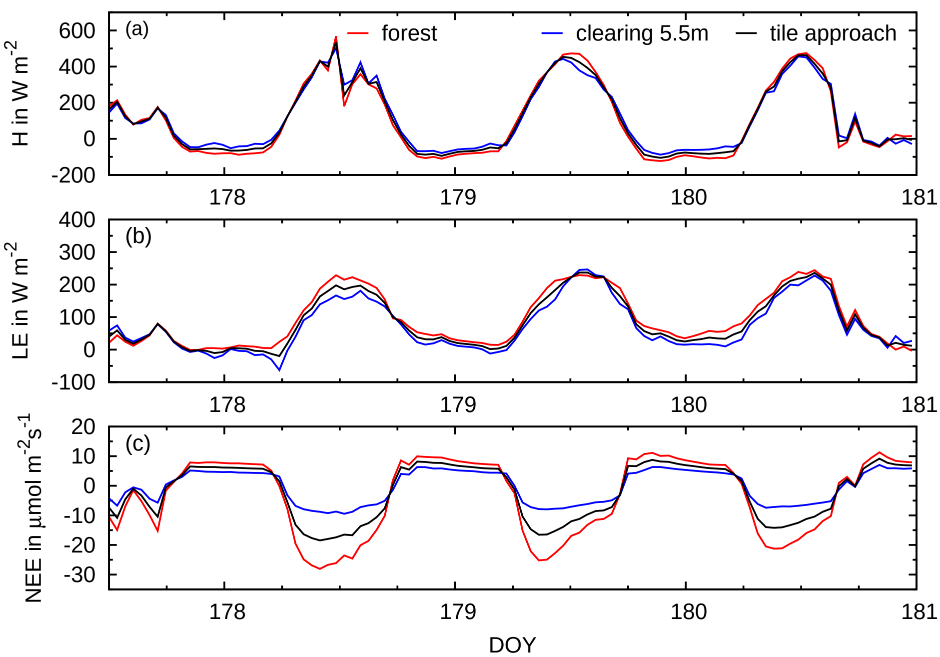

Figure 7. Main daily cycle of the a) sensible and b) latent heat flux as well as c) NEE, for the first Golden Day Period modeled with ACASA for the forest (red line) and the clearing 5.5 m (tile approach for the different land use types of the clearing; blue line) and tile approach for 50 % clearing and forest (black line).

already showed a high variation of the NEE between the different species considered in the tile approach for the clearing. This variability is also present for the comparison of the NEE for the forest and the clearing.

4 Conclusions

The ACASA model, which was originally developed for tall vegetation, can also be used with high accuracy for low vegetation if the plant specific parameters are appropriately implemented in the model. Therefore, it is applicable to consider ACASA in tile approaches for heteorogeneous areas for tall as well as short vegetation or clearings.

The footprint averaged tile approach did not show significantly better results than the tile approach for the whole clearing. The footprint model is probably not accurate enough in the location of the effect levels of the footprint, considering the small-scale heterogeneities of the clearing in comparison to the size of the footprint area. This issue has already been shown by comparison of different footprint models by Markkanen et al. (2009). For larger heterogeneities, this approach may be more appropriate. Furthermore, the clearing area contained random-like distributed very wet parts, which could not be classified in the land-use characteristics of the tile approaches.

The small underestimation by the model of fluxes above the forest is probably a local overestimation of the fluxes at the Turbulence Tower TT, which is adjacent to an area of the forest where higher fluxes are possible (Foken, 2017b). Large Eddy Simulation studies have shown that at a distance of ten times the canopy height from the forest edge, higher fluxes are possible (Kanani-Sühring and Raasch, 2015). Such a highly local effect is impossible to model in ACASA.

Assuming that the ACASA model is well parametrized and the available energy is accurately distributed to the sensible and the latent heat flux, a good agreement has been found with the energy balance corrected measurements. The correction with the buoyancy flux leads to better results, but this depends on the Bowen ratio, i.e., for $Bo > 1$ it is better than for $Bo < 1$. This result supports earlier findings (Ingwersen et al., 2011; Babel et al., 2014). The idea behind the buoyancy correction, that buoyancy is the reason for secondary circulations, is only partly true. The better correction for $Bo < 1$ with the Bowen ratio correction is not an argument for possible errors of the eddy-covariance method. Rather, the possible phase shift between the vertical wind component and the scalars, which was recently investigated by Gao et al. (2017), could be a reason. This should be an objective of a further study with a data set containing more data for $Bo < 1$. The correction of the NEE is probably useful, but the effect is not very significant for $Bo > 1$, however, it might be more applicable for accumulated fluxes.

Code and data availability. An overview of the instrumentation and important measurements at the Waldstein-Weidenbrunnen site is provided by (Foken, 2017a). Data is available from Thomas Foken on request. The ACASA model code is available from Kyaw Tha Paw U on request.

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Competing interests. The authors declare that they have no conflict of interest.

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