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Decadal water balance of a temperate Scots pine forest (*Pinus sylvestris* L.) based on measurements and modelling

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Abstract

Multi-year, multi-technique studies often yield key insights into methodological limitations but also process-level interactions that would otherwise go un-noticed if analysed at one point in time or in isolation. We examined the components of forest water balance for an 80-year-old Scots pine (*Pinus sylvestris* L.) stand in the Campine region of Belgium over a ten year period using five very different approaches; our methods ranged from data intensive measurements to process model simulations. Specifically, we used the conservative ion method (CI), the Eddy Covariance technique (EC), an empirical model (WATBAL), and two process models that vary greatly in their temporal and spatial scaling, the ORCHIDEE global land-surface model and SECRETS a stand- to ecosystem-scale biogeochemical process model. Herein we used the EC technique as a standard for the evapotranspiration (ET) estimates. We also examined ET and drainage in ORCHIDEE as influenced by climate change scenarios from the Hadley model. Results demonstrated that the two process models corresponded well to the seasonal patterns and yearly totals of ET from the EC approach. However, both WATBAL and CI approaches overestimated ET when compared to the EC estimates. Overestimation of ET by WATBAL increased as ET increased. We found positive relationships between ET and the process drivers to ET (i.e., vapour pressure deficit [VPD], mean air temperature [T_{air}], and global radiation [Rg]) for SECRETS, ORCHIDEE, and the EC estimates, though few were significant. Estimates of ET from WATBAL and the CI approach were uncoupled from VPD, T_{air}, and Rg. Independent of the method examined, ET exhibited low interannual variability. Consequently, drainage fluxes were highly correlated with annual precipitation for all five approaches examined. Estimates of ET increased in climate change scenarios for ORCHIDEE while drainage decreased.

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1 Introduction

Vegetation strongly interacts with the terrestrial water cycle to influence runoff processes within vegetated catchments (Sahin and Hall, 1996). Forests play an important role in the water and energy balance of the land surface. Complex diurnal cycles of water evaporation and energy fluxes are generated by the forest floor, and from beneath and within the forest canopy; vegetation structure and canopy height strongly influence these water cycling processes (Rutter, 1975). Consequently, forests influence the magnitude and patterns of rainfall at regional and global scale by influencing the low level moisture convergence, and they determine the amount of water that flows within the river basin (Shukla and Mintz, 1982). Long term forest monitoring sites can provide a wealth of knowledge on the drivers of the interannual and long term seasonal variation of the water balance components, such as evapotranspiration (ET) and drainage of forests. Many different approaches ranging from measurements and empirical models to generic and site parameterised process-based models have been used to estimate ecosystem water balances. The eddy covariance technique, a measurement-based approach, provides measures of latent heat flux, the energy flux density equivalent of the ET rate, and offers promising estimates for closing the water balances of ecosystems (Aubinet et al., 2000; Baldocchi and Meyers, 1998). A less common approach uses conservative ion concentrations in throughfall water and in soil water below the root zone (Eriksson and Khunakasem, 1969) to estimate ET. Finally, many different models have been used to estimate ET at the stand-scale. Empirical models, such as WATBAL, are less complicated and can calculate ET based on the Jensen and Haise equation by using a set of input parameters derived from commonly available data (Starr, 1999). Conversely, complex process-based models simulate the different subcomponents of water balance (e.g., canopy evaporation, soil evaporation, and transpiration) by using process-level algorithms. Each approach, however, has merits and drawbacks that depend on the research question and the scale of focus. Methods to estimate evapotranspiration vary in at least three ways:

1. each technique has an inherent, representative spatial and temporal scale that makes either interpolation or extrapolation necessary to make inferences outside of these scales,
2. techniques differ in whether they measure evapotranspiration or just one or several of its components, and
3. a unique set of particular assumptions, technical difficulties, measurement errors and biases are necessarily introduced with each technique employed (Wilson et al., 2001) Notwithstanding, comparing multiple approaches for one site may provide insight into the process drivers of ET and drainage over multiple spatial and temporal scales as they influence forest water balance.

The water cycle is, of course, largely determined by the climate system. Climate change (one of many global change issues) influences many more processes than the commonly reputed effects on global temperatures; associated changes in the hydrologic cycle often have even greater societal impacts than temperature through changes in precipitation, ET, runoff, and water available for human use (Chapin et al., 2008). Climate change (i.e. increased temperatures, vapour pressure deficit (VPD) and CO_2 concentrations) is projected to alter ET and, consequently, drainage from forested ecosystems (Betts et al., 2007; Teuling et al., 2009). We can study the potential effects of altered climate on forest ET by using a process based modelling approach. A better understanding of the role of vegetation in catchment hydrology can thus improve both hydrological predictions, and mitigation of global change through adaptive management strategies (Bonan, 2008; Jackson et al., 2008). The objectives of this paper are:

1. to compare and contrast measured versus modelled estimates of ET for a Scots pine forest using five approaches (SECRETS, ORCHIDEE, WATBAL, EC, CI)
2. to study the drivers of interannual variability of ET and drainage for this forest, and

3. to assess the potential impact of future climate on ET and drainage of a Scots pine forest.

2 Material and methods

2.1 Plot description

The experimental forest "De Inslag" is located in Brasschaat, 20 km NE of Antwerp in the Belgian Campine region (51°18′ N,4°31′ E). The study site consists of a 2.0 ha, 80-year-old even aged Scots pine stand situated within a 150 ha mixed coniferous/deciduous forest which is part of the ICP Forests level II and Fluxnet/CarboEurope-IP networks. The forest that surrounds the site consists of several broadleaf species, some autochthonous, such as *Betula pendula* Roth. and *Sorbus aucuparia* L., and some introduced species such as *Quercus robur* L., *Quercus rubra* L., and *Castanea sativa* Mill. The original understorey, which was comprised of, mainly, *Prunus serotina* Ehrh., was removed in 1993. Since then, a small but steady recolonisation of the shrub layer by *Betula* species and *Sorbus aucuparia* L. occurs. Following the understory removal *Molinea caerulea* L. Moench. emerges along with *Rubus* species and *Dryopteris* ferns. The site has a temperate maritime climate, with a long-term mean annual temperature of 11.1°C. The long-term mean temperatures of the coldest and warmest months are 3 and 19°C respectively, and mean annual precipitation is 824 mm. The site has a flat topography (slope: 0.3%) with an elevation of 16 m. The soil is covered with an organic surface layer of 7.5 cm depth. A deep (1.20–2.25 m) Aeolian cover sand layer (Dryas III) rests on a substratum of Clay of the Campine (40% of clay) (Tiglian) at variable depth, between 1.2 and 2.5 m and more. The soil is moist, but rarely saturated, because of rapid hydraulic conductivity in the upper horizons. A perched water table is present, varying in depth from 1 m to 2.5 m. According to the World Reference Base for Soil Resources version 2006 (WRB, 2006), the soil is classified as an Albic Hypoluvic Arenosol. The site has poor drainage because of a variable depth clay layer ranging from 1.5 m to 2 m. In 1995 tree density was 538 trees/ha^{-1}. In the winter of 1999 163 trees/ha^{-1} were harvested which decreased tree density to 375 stems/ha^{-1} (Xiao et al., 2003). Stand inventories in 2001 and 2003 indicate that no further reduction in tree density has occurred (Yuste et al., 2005).

2.2 Measurements

2.2.1 Eddy covariance approach

The vertical flux of CO_2 and H_2O above the canopy are measured using the eddy covariance technique (EC) (Baldocchi and Meyers, 1998). Fluxes of CO_2 and H_2O are measured continuously since mid 1996, using a sonic anemometer (Model SOLENT 1012R2, Gill Instruments, Lymington, UK) for wind speed and an infrared gas analyser (IRGA) (Model LI-6262, LI-COR Inc., Lincoln, NE, USA) for gaseous fluxes. Measurements are made at the top of a 41 m tower centrally located within the stand. The instruments are installed at approximately 18 m above the canopy. Detailed description of the experimental setup can be found in Kowalski (2000) and Carrara et al. (2003). Half hourly latent heat (or ET) fluxes were calculated following the recommendations of the Euroflux network (Aubinet et al., 2000; Papale et al., 2006; Reichstein et al., 2005). Gapfilling is done using mean diurnal courses (14-d moving average) and annual sums are calculated as the sum of halfhour fluxes. Only years with at least 70% of original half hourly data are considered in this analysis, thus 1998, 1999 and 2003 have no yearly EC sums.

2.2.2 Conservative ion approach

Conservative ions (CI), such as Na^+ and Cl^-, are not likely to be evaporated, therefore, their soil water concentrations increase for lower soil profiles. The difference in concentrations of CI measured in through-fall and in soil water below the root zone can thus be used to estimate the ET (Eriksson and Khunakasem, 1969). Concentra-

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tion measurements of Cl^- were done biweekly at three points within the study plot at 75 cm below soil surface and in through-fall water. Monthly seepage fluxes leaving the soil compartment were determined by multiplying the ratio of monthly chloride (Cl^-) through-fall deposition to monthly averaged Cl^- concentration with the monthly precipitation collected in the through-fall collectors below the canopy. Monthly seepage fluxes were summed to obtain the yearly seepage flux.

Chemical composition of through-fall water was sampled bimonthly with 10 systematically distributed bulk collectors in an adjacent 0.25 ha large plot. They consisted of a polyethylene funnel (14 cm ⌀) placed at a standard height of 1 m, which was connected to a subterranean 2 l polyethylene bottle. A nylon mesh was placed in the funnel to avoid contamination by large particles and debris. At every sampling, through-fall volumes from the collectors were recorded in the field and a pooled sample was taken as a weighted average from all collectors. Funnels and bottles were replaced at every sampling event. Samples were kept cool in iceboxes during transport. Fractions of chloride (Cl^-) were analysed using ion chromatography (Dionex DX-100).

2.2.3 Sap flow approach

Sap flow measurements were conducted from 26 May to 18 October 2000 using the heat field deformation (HFD) method. The HFD method is based on observed changes in an artificial heat field around a linear heater inserted into individual tree stems (Nadezhdina et al., 2006; Nadezhdina et al., 2004; Nadezhdina, 2000). Sap flow was measured on 14 representative trees which were selected based on quantils of total of a forest inventory (Xiao et al., 2003). Sap flow was scaled-up to ecosystem transpiration using basal area. A more detailed description of the measurements can be found in Verbeeck et al. (2007).

2.2.4 Empirical measurements

Empirical measurements collected for the site included estimates of soil water content (SWC), leaf area index (LAI), and meteorological data. Volumetric soil water content was measured using two series of TDR sensors (Time Domain Reflectometry), at two places within the experimental plot twice a week from 1997 to 2003 and weekly during the remaining 3 years. At each of the two sample points SWC was measured every 25 cm until a depth of 175 cm. A 10-year daily time series of projected LAI (m^2 m^{-2}) was reconstructed using a fixed seasonal pattern that was measured in 2007 (Op de Beeck et al., personal communication). Yearly maxima were derived from measurements recorded in 1999 (Gond et al., 1999), 2003 (Konopka et al., 2005) and 2007 (Op de Beeck et al., personal communication).

Meteorological data included half-hourly data recorded at the top of the tower: Global radiation (Kipp and Zonen CM6B, the Netherlands), temperature and relative humidity (Didcot Instrument Co Ltd, Abingdon, United Kingdom DTS-5A), atmospheric pressure (SETRA Barometric Pressure transducer Model 278, Setra systems, Boxborough, MA), wind speed (Didcot DWR-205G) and precipitation (Didcot DRG-51). All meteorological variables were measured at 0.1 Hz and half hourly means were stored on a data logger (Campbell CR10, UK).

Missing data for Air temperature, relative humidity, atmospheric pressure, wind speed and precipitation were obtained from a weather station at Luchtbal which is within 10 km from the research site. Because global radiation was not available at this station, it was obtained from the closest possible location which is at 50 km in Uccle.

2.3 Model descriptions

2.3.1 SECRETS

The Stand to Ecosystem CaRbon and EvapoTranspiration Simulator (SECRETS) model was written to simulate stand- to ecosystem-scale carbon and water fluxes at this research site (Sampson et al., 2001). Accordingly, SECRETS can simulate multi-species multi-structured stands; stand-scale estimates of carbon and water fluxes may result from species dependent processes occurring in the over-story, sub-story, under-story or any combination of the three depending on the stand structure simulated. Of course, SECRETS models the attenuation of light through the vegetation layers present and, thus, incident radiation to the forest floor. This biogeochemical process model estimates carbon (Sampson et al., 2006) and water (Meiresonne et al., 2003) pools and fluxes for simple (Sampson and Ceulemans, 2000) or complex (Sampson et al., 2006) species associations.

The SECRETS model simulates stand-scale carbon and water fluxes using established process algorithms adapted from several sources. Namely, the model uses maintenance respiration (R_M) and water balance formulations adapted from BIOMASS (McMurtrie and Landsberg, 1992), with photosynthesis modelled using the Farquhar formulation found in the sun/shade model (dePury and Farquhar, 1997). Soil water holding capacity is calculated from the soil sand and clay fractions following Saxton et al. (1986). Daily estimates of tissue-specific R_M are derived by integration using diurnal trends in temperature and estimates of standing mass in standard Q_{10} equations. Transpiration and evaporation estimates are derived from integration using Penman-Monteith equations however under-story estimates are based on formulations by Kelliher et al. (1986). Daily estimates of transpiration are calculated from hourly estimates of water vapour conductance using the Ball-Woodrow-Berry model adapted by Leuning (1995). The SECRETS model simulates photosynthesis for both sun and shade leaves and needles on an hourly (or half-hourly) time-step. Although most process-level outputs are available for these analyses we focused on the components of water balance that included canopy interception, evaporation, transpiration, throughfall, stem flow, and surface and soil water evaporation (all in units of mm d^{-1}). A flow diagram of the model may be found in Sampson et al. (2001).

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2.3.2 ORCHIDEE

ORCHIDEE (Krinner et al., 2005) is a process-oriented integrated global land-surface model consisting of three sub modules: a global land surface scheme (Ducoudre et al., 1993) and a global continental carbon cycle model. The model simulates the diurnal cycle of turbulent fluxes of CO_2, water, and energy, while the ecosystem carbon and water dynamics (i.e., carbon allocation, plant respiration, growth, mortality, soil organic matter decomposition, water infiltration and runoff) are calculated at a daily time step. As in most global biogeochemical models, Plant Functional Types (PFTs) are used to classify vegetation at any particular site. ORCHIDEE simulates 13 PFTs at the globe scale, with all PFTs sharing the same equations but using different parameter values. Plant phenology is one exception, where PFT-specific equations exist (Botta et al., 2000). For this study ORCHIDEE was run at local scale ("grid point mode") using the half-hourly meteorological forcing measured at the site. We used the "temperate evergreen needle-leaf forest", a PFT found in ORCHIDEE, as a surrogate for the Scots pine at Brasschaat for which the standard parameter values were used. Phenology was simulated prognostically with a prescribed maximum LAI. We initialized biomass and soil carbon pools to equilibrium values from a 2000 year long spin-up driven by cycling the 10 year available climate inputs.

2.3.3 WATBAL

WATBAL (Starr, 1999) uses water balance calculations typically found in simple temperature-based models (Thornthwaite and Mather, 1957; Xu and Singh, 1998), however potential ET in WATBAL is estimated from global radiation and based on the relationship between air temperature and the ratio between evaporation and global radiation – or the Alfalfa reference method – as found in Jensen and Haise (1963). It calculates evaporative heat flux density, which is then converted into mm of potential ET using the latent heat of vaporization (De Vries et al., 2007). A crop factor, as described in Meiresonne et al. (2003), uses a seasonal pattern in values that range between 1.07 and 1.18 to convert potential evaporation for the reference crop into one for forest. ET is then computed by comparing water supply with water demand, taking into account soil water availability. Although WATBAL was principally based on an end-of-the-month book keeping methodology, Starr (unpublished data) altered the model to enable daily simulations of soil water balance for several water balance components: daily precipitation inflow, daily drainage (soil water flux) and ET outflows, and daily changes in soil water storage. WATBAL uses daily mean air temperature, precipitation and global radiation (or cloud cover) as meteorological input.

2.4 Water balance

Water balance estimates for the five approaches range greatly from pure data driven methods (CI and EC) to an empirical approach (WATBAL), to process models (ORCHIDEE and SECRETS) (Fig. 1). All five approaches gave us an estimate for ET, which was then used to calculate the drainage based on the water balance equation:

$$P = ET + \text{drainage} \pm \Delta SWC + R \tag{1}$$

Where: P is total precipitation (mm a^{-1}), ET (mm a^{-1}) was previously described, ΔSWC is the difference in soil water content and R is runoff (mm a^{-1}). For these analyses we assume that R is equal to zero because of the high hydraulic conductivity of the soil and no sloping terrain at our site. In addition to daily estimates of ET the two process models, ORCHIDEE and SECRETS, also estimated transpiration, soil evaporation, and canopy evaporation.

2.5 Future climate predictions

Future regional climate predictions were obtained from the Hadley model simulations for the A2 and B2 IPCC AR4 scenarios for the period 2070–2100. The model outputs used in these analyses included current and future daily absolute values for mean temperature, precipitation, relative humidity, and global radiation. The simulations were performed for the European continent with a 0.5° grid scale resolution. Because the model runs consisted of current and future climate predictions, perturbation factors were calculated by dividing the future runs by the current runs for each meteorological measurement. We calculated the mean seasonal patterns in the perturbation factors using the 30 years series. These values were then multiplied by the current meteorological data measured at the study site to provide an estimate of the expected, future, meteorology.

The Hadley model was chosen because it was the only one that provided future predictions of relative humidity, which, in combination with future temperature, was used to calculate vapour pressure deficit (VPD). Future expected changes in precipitation were calculated in a similar way as the other variables, but on a monthly time scale. To account for increasing summer droughts, all precipitation events smaller than 2 mm were removed and accumulated on the next rain event with more than 2 mm. This was only done in months were there was a relative decrease in precipitation. Future predicted CO_2-concentrations from the A2 and B2 scenario were used for the 2070–2080 period as input. The ORCHIDEE model was used to simulate the water balance with the predicted future climate input variables. To be able to estimate the effect of future climate on the water balance the same spinup was used for the contemporary climate simulations.

3 Results

3.1 Climatic conditions

Rainfall varied considerably during the course of this investigation (Fig. 2). Of the ten years examined, the driest year was 1997 which exhibited a total rainfall of 671 mm; 201 mm (30%) fell during the growing season (which generally starts in April and lasts until October). In contrast, the wettest year was 1998, with a total of 1041 mm, of which 248 mm (28%) fell during the growing season. Mean yearly temperature was the lowest in 1997 (10.6°C) and highest in 2006 (11.9°C). The coldest month was observed in January 1997, with mean monthly temperature of −0.8°C. The warmest month was measured in July 2006, with a mean monthly temperature of 22.4°C (Fig. 2).

Distinct diurnal and seasonal patterns in the meteorological variables that drive water flux and, thus, site water balance were evident for our site (Fig. 3). More narrowly defined growing season air temperature (T_{air}) profiles for 1998 and 2002 (Fig. 3) corresponded to greater than average precipitation for those years (Fig. 2). Note that there were no EC measurements available for 1998, 1999, and 2003.

3.2 Model evaluation

Model simulations suggest that transpiration represented the dominant portion of the annual ET flux (on average, 55% for SECRETS and 65% for ORCHIDEE). Therefore, the simulated transpiration was evaluated with estimates of transpiration from sap flow data (Fig. 4). ORCHIDEE overestimated the measured sap flow by 8% (R^2=0.76) while SECRETS underestimated measured sap flow by, on average, 14% (R^2=0.67). Total stand-scale ET simulated by the models was compared to monthly estimates of the latent heat fluxes (Fig. 5). Results indicated that both SECRETS and ORCHIDEE performed well, although both models slightly overestimated ET in the lower range up to 0.5 mm d^{-1}. SECRETS demonstrated good correspondence to the measured latent heat flux (R^2=0.69), overestimating ET by only 1%. ORCHIDEE overestimated the latent heat fluxes by 5% but with less variance (R^2=0.86). On average, estimates obtained from WATBAL were 73% (R^2=0.82) greater than the measured latent heat fluxes.

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3.3 Approach comparison

3.3.1 Annual estimates

Box and wisker plots of the seven-year mean annual ET (recall, we have no EC data for 1998, 1999 and 2003) for the five methods indicated that the EC approach produced the lowest estimates (264±43 mm), followed by the two processes models ORCHIDEE (291±28 mm) and SECRETS (304±28 mm) (Fig. 6a). WATBAL (475±30 mm) and CI (505±77 mm) both overestimated ET when compared to the EC measurements. Simulation and measurements results for drainage were the opposite; estimates of latent heat fluxes from the EC approach were highest (556±130 mm) of the five methods examined, followed by SECRETS (516±129 mm) and then ORCHIDEE (529±137 mm). Finally, WATBAL (346±134 mm) and CI (310±101 mm) underestimated drainage when compared to the EC measurements.

3.3.2 Seasonal patterns

We used the seven-year mean monthly estimates of ET and drainage to calculate seasonal patterns in these fluxes for all methods except the CI approach. Season patterns were not possible for the CI estimates because of the irregular sampling methodology. Results (Fig. 7a) show that ET reached a maximum in mid-summer (Fig. 3c). WATBAL followed the same seasonal trends as the other approaches but estimated ca. 67% more ET (2.4 mm d^{-1} compared to ca. 1.5 mm d^{-1}) than the process models. The process model estimates of monthly ET were comparable to those measured by the EC approach (Fig. 7a). A monthly mean maximum of 1.5 mm $d^{-1}$was observed. Because precipitation was evenly distributed throughout the year (data not shown), the seasonal trends of drainage followed an inverse pattern than that of ET (Fig. 7b). Drainage reached a monthly mean maximum in October, varying from 1.5 mm d^{-1} for WATBAL, 2.7 mm d^{-1} for SECRETS, 1.7 mm d^{-1} for the EC fluxes, and 1.8 mm d^{-1} for ORCHIDEE. The monthly mean minimum was achieved in June due to the high ET for the month. The relative difference between the approaches was highest in summer where the difference in ET estimates was also the highest WATBAL reached a monthly mean minimum drainage of 0 mm d^{-1} while the process models and the EC fluxes did not drop below 1 mm d^{-1}.

3.4 Drivers of interannual variability

Total global radiation (Fig. 8a), mean air temperature Fig. 8b), and mean vapour pressure deficit (VPD) (Fig. 8c) were used to examine the functional relationships of ET to the process drivers for each of the five approaches. Linear regression analyses demonstrated that, although very few relationships were statistically significant, the best fits as evaluated using the coefficient of determination (R^2) were found for the process models (Table 1). Overall the lowest R^2 were found for the estimates from WATBAL, except for total global radiation where EC has the lowest R^2 (Table 1).

Interannual variability in drainage, for all approaches, was highly correlated with yearly precipitation (Fig. 8d; Table 2). The CI method was the only approach that exhibited a negative slope for the regression between ET and all three variables: total global radiation, mean air temperature, and mean vapour pressure deficit.

3.5 Responses to future climate

Results from the Hadley model show a temperature increase for Flanders between 1 and 1.9°C for the B2 scenario and between 2 and 3°C for the A2 scenario (Fig. 9a). These temperature departures resulted in a 0.1 kPa and a 0.2 kPa increase in daily maximal VPD (Fig. 9b). The seasonal patterns in precipitation for both scenarios (Fig. 9c) are variable, but different from the current pattern (Fig. 2). Based on these climate projections winter precipitation would increase by up to 60% and 21%, respectively, for A2 and B2 scenarios while summers could be as much as 58% and 42% drier, respectively (Fig. 9c).

ORCHIDEE model results indicate that ET increased in both A2 (+17%) and B2 (+14%) scenarios (Fig. 10a). Drainage decreased 28% in A2 and 27% in B2 climate projections (Fig. 10b). The absolute change in drainage was, again, opposite when compared to the ET for both scenarios (Fig. 10b). The larger change in drainage compared to the increase in ET is partly due to the change in yearly total precipitation which is −11% for A2 scenario and −12% for B2 scenario (data not shown). Additionally, due to the altered seasonal pattern of precipitation the drainage decreased significantly in summer and increased in winter (data not shown).

4 Discussion

With the exception of the CI method and WATBAL, our estimates of ET fall within the range of previously reported values. Verstraeten et al. (2005) estimated a yearly ET of 314 mm for our study site using the empirical model WAVE (Vanclooster et al., 2000). Amiro et al. (2006) found ET to range from 252 to 267 mm year^{-1} for a young jack pine stand in central Canada using eddy covariance (EC) techniques. Granier et al. (2008) reported a 10-year mean ET of 334 mm a^{-1} for a mature beech stand in the north east of France measured with EC. Our estimates are a bit low when compared to others which can be, in part, attributed to the very low LAI at our site. The proportion of transpiration to ET (0.55 to 0.65) as estimated by OCHIDEE and SECRETS is also comparable to literature values. McLaren et al. (2008) reported that 47% of ET could be attributed to transpiration, Oren et al. (1998) reported that transpiration accounted for 69% of ET in a temperate Loblolly pine (*Pinus taeda* L.) plantation in North Carolina, USA. Unsworth et al. (2004) reported transpiration to be 65% of ET in a temperate Douglas fir – Western hemlock (*Pseudotsuga menziesii* – *Tsuga heterophylla*) old growth forest, and Grelle et al. (1997) reported 75% in a boreal mixed conifer (*Picea abies* – *Pinus sylvestris* L.) forest. Finally, Kurpius et al. (2003) found that 53% of ET came from transpiration in a Ponderosa pine (*Pinus ponderosa* Laws) plantation in California, USA.

The sigmoid shape of the relationship between simulated transpiration and that measured from sap flow may, in part, be due to storage effects in the stem (Fig. 4). This would indicate that transpiration was under-estimated by sap flow measurements on days with high atmospheric demand, and over-estimated on days with low atmospheric pressure. On days with high atmospheric demand, some of the transpired water could come from storage in the stem as observed by Verbeeck et al. (2007).

Comparing the five different approaches we find relatively good agreement between the two process models (SECRETS and ORCHIDEE) and the EC method. The difference in the residuals in the relationship between ET simulated by the models and the EC fluxes could be due to several reasons (Fig. 5). First, the discrepancy between the seasonal patterns of ET from both models and the EC measurements could be attributed to the absence of understorey ET in the model simulations. Due to a change in forest management this understorey, which was removed in the past, has emerged since the beginning of period of this study. It is not possible to reconstruct the succession of this vegetation layer and thus the contribution of the understorey at a given time. Hence, we are not able to give an estimate for the contribution of understorey ET to total stand ET. Omitting the understorey in the model simulation could lead to a significant underestimation of ET. Granier et al. (1989) cited a contribution of 10% for bilberry understory (*Vaccinium myrtillus* L.) in a Scots pine forest and Jarosz et al. (2008) reported a contribution of 38% for purple moor-grass (*Molinia coerulea* L. Moench.) under a maritime Pine forest (*Pinus pinaster* Ait.). However, there could be a trade-off with the simulated soil evaporation. Especially because the contribution of the soil evaporation is high because of the rather low LAI (Wullschleger et al., 1998). A second reason for this deviation could be due to phenology, because a fixed seasonal LAI pattern that was measured in 2007 was used for SECRETS for the 10 year period and ORCHIDEE has a sub module that simulates the LAI pattern with a maximum of 1.8. This value was the maximum peak-LAI that was measured within the 10 years period. Both approaches could cause uncertainties in the seasonal pattern compared to the EC measurements. A third possible explanation could be the fact that the EC measurements comprise patches with other tree species, grasses and heathland. The influence of those patches could alter the correlation between the measured fluxes and the model results which are species-specific. Finally, the EC fluxes could underestimate ET because of a lack in energy balance closure (Foken, 2008; Ibrom et al., 2007). Several studies (Falge et al., 2005; Loescher et al., 2005) have countered this problem by estimating the latent heat fluxes as a residual of the energy balance. Since the mean energy balance closure was only 63±7%, we decided not to use this method as it would probably overestimate the latent heat flux (Amiro, 2009).

The empirical WATBAL model produces relatively high estimates of ET with an average overestimate of 73% when compared to the EC fluxes (Fig. 6). The seasonal course of ET shows that the overestimate occurred mostly in summer, while in winter the ET is slightly lower than the EC (Fig. 7). The overall larger estimates of ET by WATBAL could result from the relatively high crop factor (Kc) that is applied in the calculations. Although the Kc factor is obtained from a similar forest site in Belgium, obviously this Kc factor has a large impact on the estimates of ET and could introduce a large uncertainty. The CI method is considered less useful for these studies as our results show that the ET is overestimated by 92% when compared to the EC method (Fig. 6a). Additionally, when looking at the drivers of ET, the estimates for the CI method show a negative relation mean annual temperature, VPD and total global radiation. These odd findings can be explained by the presence of a different autocorrelation structure in the chloride time series from soil solution chemistry compared to throughfall chemistry. Additionally, the start and end of the sampling dates varies too much to allow a robust intercomparison on monthly basis.

Few significant correlations are found for the expected drivers of ET estimates by the four remaining approaches. These relations are based on yearly averages or sums and thus could be weakened by the large dormant season. In contrast, all five approaches show a very strong relation between yearly precipitation and drainage. The slope of the curve varies between 0.62 for CI and 0.89 for ORCHIDEE. These strong relations could be explained by the fact that the variation in ET is limited compared to that of precipitation. Consequently, all the excess water is leached out of the ecosystem.

Since our study site is located in a region with ample supply of water, the ET is clearly related to the atmospheric demand (e.g. VPD) and not to water supply (Teuling et al., 2009). Overall, despite the method, the interannual variability in ET over an extensive period of seven year is rather limited. To the authors knowledge only three recent studies have reported long term annual sums of ET measured with eddy covariance. Granier et al. (2008) measured 10 years of ET over a beech forest in Hesse (France), Grunwald and Bernhofer (2007) reported 9 years of ET measured over a spruce forest (*Picea abies* L.) in Tharandt (Germany) and Ohta et al. (2008) measured ET for 7 years over a larch forest (*Larix cajanderi* Mayr.) in Siberia. All studies find a low interannual variability in ET with mean annual sum and standard deviation of 334±62 mm and 475±45 mm and 196±19 mm, respectively.

5 Conclusions

Although there are several methods to estimate forest water balance, our results suggest that the approach used, and the component examined, must both be considered when choosing a method for study. In this study we compared five commonly used approaches to estimate site water balance. Eddy covariance (EC) estimates of ET are often considered a standard for which to compare alternate approaches. Our results suggest that process model simulations from SECRETS and ORCHIDEE corresponded well to the EC estimates, both on an annual basis and for interannual comparisons. Yearly and seasonal patterns were maintained for both models although the models both slightly overestimated annual ET. The Conservative Ion method and WATBAL both overestimated ET.

Few significant relationships could be found between ET and the processes that drive ET (i.e., VPD. Air temperature, and global radiation); small inter-annual variability in total yearly ET was observed. Consequently, drainage estimated by all five approaches was strongly correlated with annual precipitation. The effect of future climate on total

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ET shows that ET will increase due to higher evaporative demand, although the effect is limited. This will result in decreasing drainage.

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References

Amiro, B.: Measuring boreal forest evapotranspiration using the energy balance residual, J. Hydrol., 366, 112–118, 2009.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, in: Advances in Ecol. Res., Vol. 30, Academic Press Inc, San Diego, 113–175, 2000.

Baldocchi, D. and Meyers, T.: On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: a perspective, Agr. Forest Meteorol., 90, 1–25, 1998.

Betts, R. A., Boucher, O., Collins, M., Cox, P. M., Falloon, P. D., Gedney, N., Hemming, D. L., Huntingford, C., Jones, C. D., Sexton, D. M. H., and Webb, M. J.: Projected increase in continental runoff due to plant responses to increasing carbon dioxide, Nature, 448, 1037–1041, 2007.

Bonan, G. B.: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests, Science, 320, 1444–1449, 2008.

Botta, A., Viovy, N., Ciais, P., Friedlingstein, P., and Monfray, P.: A global prognostic scheme of leaf onset using satellite data, Glob. Change Biol., 6, 709–725, 2000.

Carrara, A., Kowalski, A. S., Neirynck, J., Janssens, I. A., Yuste, J. C., and Ceulemans, R.: Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years, Agr. Forest Meteorol., 119, 209–227, 2003.

Chapin, F. S., Randerson, J. T., McGuire, A. D., Foley, J. A., and Field, C. B.: Changing feedbacks in the climate-biosphere system, Front. Ecol. Environ., 6, 313–320, doi:10.1890/080005, 2008.

De Vries, W., Wamelink, W., Reinds, G. J., Wieggers, H. J. J, Mol-Dijkstra, J. P., Kros, J., Nabuurs, G. J., Pussinen, A., Solberg, S., Dobbertin, M., Laubhann, D., Sterba, H., and Oijen, M.: Assessment of the relative importance of nitrogen deposition climate change and forest management on the sequestration of carbon by forests in Europe, Alterra, Wageningen, 302 pp. (361 Figs., 394 Tables, 469 Refs.), 2007.

dePury, D. G. G. and Farquhar, G. D.: Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models, Plant. Cell. Environ., 20, 537–557, 1997.

Ducoudre, N. I., Laval, K., and Perrier, A.: Sechiba, a New Set of Parameterizations of the Hydrologic Exchanges at the Land Atmosphere Interface within the Lmd Atmospheric General-Circulation Model, J. Climate, 6, 248–273, 1993.

Eriksson, E. and Khunakasem, V.: Chloride concentration in groundwater, recharge rate and rate of deposition of chloride, J. Hydrol., 7, 178–197, 1969.

Falge, E., Reth, S., Bruggemann, N., Butterbach-Bahl, K., Goldberg, V., Oltchev, A., Schaaf, S., Spindler, G., Stiller, B., Queck, R., Kostner, B., and Bernhofer, C.: Comparison of surface energy exchange models with eddy flux data in forest and grassland ecosystems of Germany, Ecol. Model., 188, 174–216, 2005.

Foken, T.: The energy balance closure problem: An overview, Ecol. Appl., 18, 1351–1367, 2008.

Gond, V., de Pury, D. G. G., Veroustraete, F., and Ceulemans, R.: Seasonal variations in leaf area index, leaf chlorophyll, and water content; scaling-up to estimate fAPAR and carbon balance in a multilayer, multispecies temperate forest, Tree Physiol., 19, 673–679, 1999.

Granier, A., Loustau, D., Saugier, B., and Berbigier, P.: Bilan hydrique de deux peuplements de pin maritime dans les Landes : évaluation des flux des strates ligneuse et herbacée et de leur variabilité., in: ATP PIREN, Influence à l'échelle régionale des couvertures pédologiques et végétales sur les bilans hydriques et minéraux du sol., 287–315, 1989.

Granier, A., Breda, N., Longdoz, B., Gross, P., and Ngao, J.: Ten years of fluxes and stand growth in a young beech forest at Hesse, North-eastern France, Ann. For. Sci., 65, 704, 2008.

Grelle, A., Lundberg, A., Lindroth, A., Morén, A. S., and Cienciala, E.: Evaporation components of a boreal forest: variations during the growing season, J. Hydrol., 197, 70–87, 1997.

Grunwald, T. and Bernhofer, C.: A decade of carbon, water and energy flux measurements of an old spruce forest at the Anchor Station Tharandt, Tellus Ser. B-Chem. Phys. Meteorol., 59, 387–396, 2007.
Ibrom, A., Dellwik, E., Flyvbjerg, H., Jensen, N. O., and Pilegaard, K.: Strong low-pass filtering effects on water vapour flux measurements with closed-path eddy correlation systems, Agr. Forest Meteorol., 147, 140–156, 2007.
Jackson, R. B., Randerson, J. T., Canadell, J. G., Anderson, R. G., Avissar, R., Baldocchi, D. D., Bonan, G. B., Caldeira, K., Diffenbaugh, N. S., Field, C. B., Hungate, B. A., Jobbagy, E. G., Kueppers, L. M., Nosetto, M. D., and Pataki, D. E.: Protecting climate with forests, Environ. Res. Lett., 3, 044006, doi:044010.041088/041748-049326/044003/044004/044006, 2008.
Jarosz, N., Brunet, Y., Lamaud, E., Irvine, M., Bonnefond, J.-M., and Loustau, D.: Carbon dioxide and energy flux partitioning between the understorey and the overstorey of a maritime pine forest during a year with reduced soil water availability, Agr. Forest Meteorol., 148, 1508–1523, 2008.
Jensen, M. E. and Haise, H. R.: Estimating evapotranspiration from solar radiation, J. Irrig. Drain. E., 89, 15–41, 1963.
Kelliher, F. M., Black, T. A., and Price, D. T.: Estimating the Effects of Understory Removal from a Douglas-Fir Forest Using a 2-Layer Canopy Evapotranspiration Model, Water Resour. Res., 22, 1891–1899, 1986.
Konopka, B., Yuste, J. C., Janssens, I. A., and Ceulemans, R.: Comparison of fine root dynamics in scots pine and pedunculate oak in sandy soil, Plant Soil, 276, 33–45, 2005.
Kowalski, A. S., Overloop, S., Ceulemans, R.: Eddy fluxes above a Belgian, Campine forest and their relationship with predicting variables, in: Forest Ecosystem Modelling, Upscaling and Remote Sensing, edited by: Ceulemans, R., Veroustraete, F., Gond, V., Van Rensbergen, J., SPB Academic Publishing, The Hague, The Netherlands, 3–17, 2000.
Krinner, G., Viovy, N., de Noblet-Ducoudre, N., Ogee, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Glob. Biogeochem. Cy., 19, GB1025, doi:1010.1029/2003GB002199, 2005.
Kurpius, M. R., Panek, J. A., Nikolov, N. T., McKay, M., and Goldstein, A. H.: Partitioning of water flux in a Sierra Nevada ponderosa pine plantation, Agr. Forest Meteorol., 117, 173–192, 2003.
Leuning, R.: A Critical-Appraisal of a Combined Stomatal-Photosynthesis Model for C-3 Plants,

Plant Cell Environ., 18, 339–355, 1995.
Loescher, H. W., Gholz, H. L., Jacobs, J. M., and Oberbauer, S. F.: Energy dynamics and modeled evapotranspiration from a wet tropical forest in Costa Rica, J. Hydrol., 315, 274–294, 2005.
McLaren, J. D., Arain, M. A., Khomik, M., Peichl, M., and Brodeur, J.: Water flux components and soil water-atmospheric controls in a temperate pine forest growing in a well-drained sandy soil, J. Geophys. Res., 113, G04031, doi:04010.01029/02007JG000653, 2008.
McMurtrie, R. E. and Landsberg, J. J.: Using a simulation model to evaluate the effects of water and nutrients on the growth and carbon partitioning of Pinus radiata, Forest Ecol. Manag., 52, 243–260, 1992.
Meiresonne, L., Sampson, D. A., Kowalski, A. S., Janssens, I. A., Nadezhdina, N., Cermak, J., Van Slycken, J., and Ceulemans, R.: Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches, J. Hydrol., 270, 230–252, 2003.
Nadezhdina, N., Tributsch, H., and Cermak, J.: Infra-red images of heat field around a linear heater and sap flow in stems of lime trees under natural and experimental conditions, Ann. For. Sci., 61, 203–213, 2004.
Nadezhdina, N., Cermak, J., Gasparek, J., Nadezhdin, V., and Prax, A.: Vertical and horizontal water redistribution in Norway spruce (Picea abies) roots in the Moravian Upland, Tree Physiol., 26, 1277–1288, 2006.
Nadezhdina, N. a. J. C.: The technique and instrumentation for estimation the sap flow rate in plants, Patent No. 286438 (PV-1587-98), 2000.
Ohta, T., Maximov, T. C., Dolman, A. J., Nakai, T., van der Molen, M. K., Kononov, A. V., Maximov, A. P., Hiyama, T., Iijima, Y., Moors, E. J., Tanaka, H., Toba, T., and Yabuki, H.: Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006), Agr. Forest Meteor., 148, 1941–1953, 2008.
Oren, R., Phillips, N., Katul, G., Ewers, B. E., and Pataki, D. E.: Scaling xylem sap flux and soil water balance and calculating variance: a method for partitioning water flux in forests, Ann. Sci. For., 55, 191–216, 1998.
Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeosciences, 3, 571–583, 2006, http://www.biogeosciences.net/3/571/2006/.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Glob. Change Biol., 11, 1424–1439, 2005.

Rutter, A.: The hydrological cycle vegetation, in: Vegetation and atmosphere, Vol. I, edited by: Montheith, J. L., Academic Press, London, 111–154, 1975.

Sahin, V. and Hall, M. J.: The effects of afforestation and deforestation on water yields, J. Hydrol., 178, 293–309, 1996.

Sampson, D. A. and Ceulemans, R.: SECRETS: simulated carbon fluxes from a mixed coniferous/deciduous forest in: In Forest Ecosystem Modeling, Upscaling and Remote Sensing, 95–108, 2000.

Sampson, D. A., Janssens, I. A., and Ceulemans, R.: Simulated soil CO2 efflux and net ecosystem exchange in a 70-year-old Belgian Scots pine stand using the process model SECRETS, Ann. For. Sci., 58, 31–46, 2001.

Sampson, D. A., Janssens, I. A., and Ceulemans, R.: Under-story contributions to stand level GPP using the process model SECRETS, Agr. Forest Meteorol., 139, 94–104, 2006.

Saxton, K. E., Rawls, W. J., Romberger, J. S., and Papendick, R. I.: Estimating Generalized Soil-Water Characteristics from Texture, Soil Sci. Soc. Am. J., 50, 1031–1036, 1986.

Shukla, J. and Mintz, Y.: Influence of Land-Surface Evapo-Transpiration on the Earths Climate, Science, 215, 1498–1501, 1982.

Starr, M.: A model for estimating monthly water balance components, including soil water fluxes, in: 8th Annual Report 1999, ICP Integrated Monitoring, edited by: Kleemola, S. and Forsius, M., Finnish Environment Institute, Helsinki, Finland, 31–35, 1999.

Teuling, A. J., Hirschi, M., Ohmura, A., Wild, M., Reichstein, M., Ciais, P., Buchmann, N., Ammann, C., Montagnani, L., Richardson, A. D., Wohlfahrt, G., and Seneviratne, S. I.: A regional perspective on trends in continental evaporation, Geophys. Res. Lett., 36, L02404, doi:02410.01029/02008GL036584, 2009.

Thornthwaite, C. W. and Mather, J. R.: Instructions and tables for computing potential evapotranspiration and the water balance, Laboratory of Climatology, Centerton, NJ, 1957.

Unsworth, M. H., Phillips, N., Link, T., Bond, B. J., Falk, M., Harmon, M. E., Hinckley, T. M.,

Marks, D., and U, K. T. P.: Components and controls of water flux in an old-growth Douglas-fir-western hemlock ecosystem, Ecosystems, 7, 468–481, 2004.
Vanclooster, M., Viaene, P., Diels, J., and Christiaens, K.: WAVE, a mathematical model for simulating water and agrochemicals in the soil and vadose environment. Reference and user's manual, Release 2.0., Institute for Land and Water Management, Katholieke Universiteit Leuven, Leuven, 144 pp., 2000.
Verbeeck, H., Steppe, K., Nadezhdina, N., Op de Beeck, M., Deckmyn, G., Meiresonne, L., Lemeur, R., Cermak, J., Ceulemans, R., and Janssens, I. A.: Stored water use and transpiration in Scots pine: a modeling analysis with ANAFORE, Tree Physiol., 27, 1671–1685, 2007.
Verstraeten, W. W., Muys, B., Feyen, J., Veroustraete, F., Minnaert, M., Meiresonne, L., and De Schrijver, A.: Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE, Hydrol. Earth Syst. Sci., 9, 225–241, 2005, http://www.hydrol-earth-syst-sci.net/9/225/2005/.
Wilson, K. B., Hanson, P. J., Mulholland, P. J., Baldocchi, D. D., and Wullschleger, S. D.: A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance, Agr. Forest Meteorol., 106, 153–168, 2001.
WRB, I. W. G.: World reference base for soil resources, 2nd Edn., World soil resources reports no. 103, FAO, Rome, 2006.
Wullschleger, S. D., Hanson, P. J., and Tschaplinski, T. J.: Whole-plant water flux in understory red maple exposed to altered precipitation regimes, Tree Physiol., 18, 71–79, 1998.
Xiao, C. W., Yuste, J. C., Janssens, I. A., Roskams, P., Nachtergale, L., Carrara, A., Sanchez, B. Y., and Ceulemans, R.: Above- and belowground biomass and net primary production in a 73-year-old Scots pine forest, Tree Physiol., 23, 505–516, 2003.
Xu, C. Y. and Singh, V. P.: A Review on Monthly Water Balance Models for Water Resources Investigations, Water Resour. Manage., 12, 20–50, 1998.
Yuste, J. C., Konopka, B., Janssens, I. A., Coenen, K., Xiao, C. W., and Ceulemans, R.: Contrasting net primary productivity and carbon distribution between neighboring stands of Quercus robur and Pinus sylvestris, Tree Physiol., 25, 701–712, 2005.

Table 1. Coefficients for the linear regression analyses between ET (mm a^{-1}) estimated by the five different approaches (SECRETS, ORCHIDEE, WATBAL, eddy covariance [EC] and conservative ion [CI]) and the process drivers (i.e., VPD; kPa, mean daily air temperature [T_{air}; Celsius] and global radiation [Rg; MJ m^{-2} a^{-1}] for each of the five methods. In all cases the model used was: $y(x) = a * x + b$. Included in the table are estimates of the coefficient of determination (R^2) and the p-values for each regression analysis.

	VPD				T_{air}				Rg			
	b	a	R^2	p-value	b	a	R^2	p-value	b	a	R^2	p-value
SECRETS	224.2	288.6	0.41	0.05	−93.7	36.8	0.39	0.05	59.0	0.07	0.31	0.09
ORCHIDEE	184.4	378.6	0.51	0.02	−243.4	49.3	0.51	0.02	−90.9	0.11	0.54	0.02
WATBAL	453.2	10.8	0.00	0.96	397.5	5.3	0.01	0.84	494.2	−0.01	0.00	0.85
EC	169.5	341.2	0.43	0.11	−266.2	48.9	0.53	0.06	−132.3	0.11	0.09	0.53
CI	636.4	−408.3	0.16	0.25	1133.6	−56.3	0.18	0.22	1060.2	−0.15	0.29	0.11

Table 2. Coefficients for the linear regression analyses between precipitation (mm a^{-1}) and drainage (mm a^{-1}) for the five approaches (SECRETS, ORCHIDEE, WATBAL, eddy covariance [EC] and conservative ion [CI]). Included in the table are estimates of the coefficient of determination (R^2) and the p-values for each regression analysis.

	b	*a*	R^2	p-value
SECRETS	−16.6	0.65	0.71	0.002
ORCHIDEE	−60.9	0.72	0.74	0.002
WATBAL	−174.8	0.67	0.55	0.014
EC	−166.7	0.88	0.74	0.013
CI	63.4	0.33	0.17	0.232

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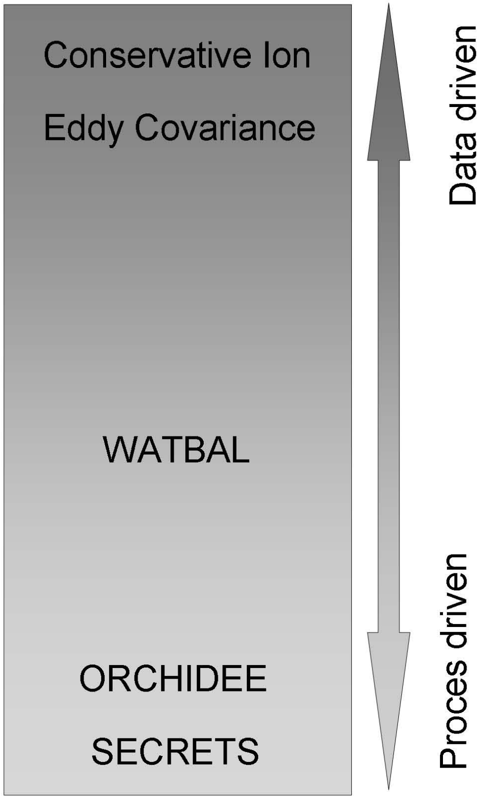

Fig. 1. Overview of the five different approaches used in this study. The methods used vary greatly, ranging from data intensive measurements (Chloride method) to process simulation (SECRETS).

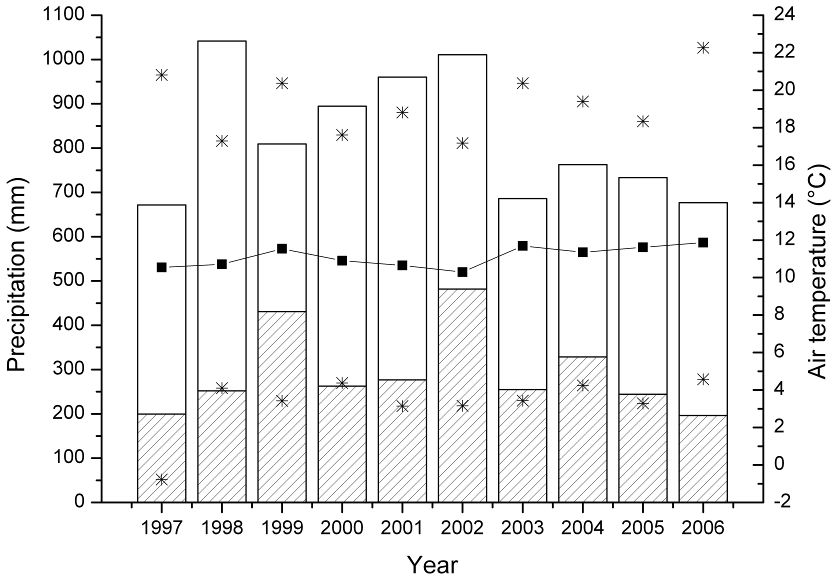

Fig. 2. Summary of the meteorological data measured on a 41 m centrally located tower within the study site during the period from 1997 through 2006 (abscissa). The left ordinate axis displays yearly precipitation (mm) during the growing season (dashed bar graph) and the dormant season (open bars). The right ordinate displays average yearly temperature (˚C) (line graph: asterisks indicate lowest and highest mean monthly temperatures).

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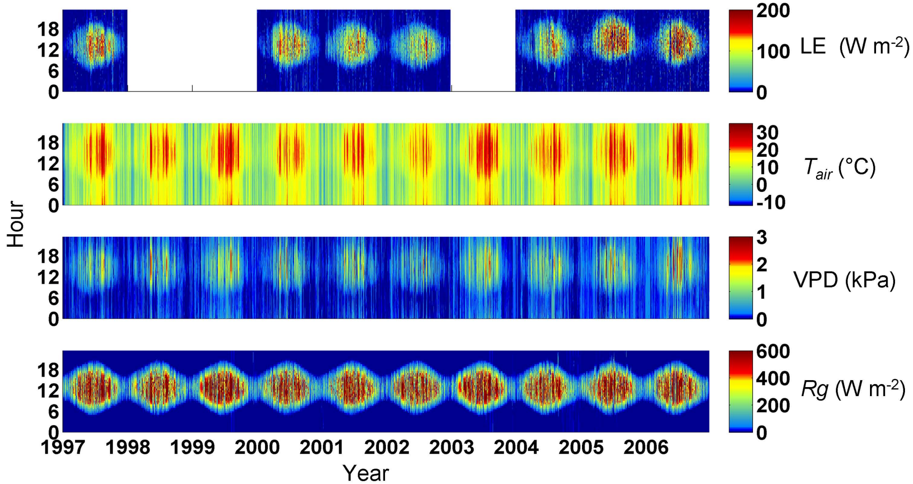

Fig. 3. Latent heat (LE-W m^{-2}), air temperature (T_{air}-°C), vapour pressure deficit (VPD-kPa) and incident (global) radiation (Rg-W m^{-2}) during the study period. Data reflect half-hourly measurements from the top of a 41 m tower located within the study site by year (abscissa) and hour of the day (ordinate). The color bar at the right of the figure indicates the magnitude of the response for each variable.

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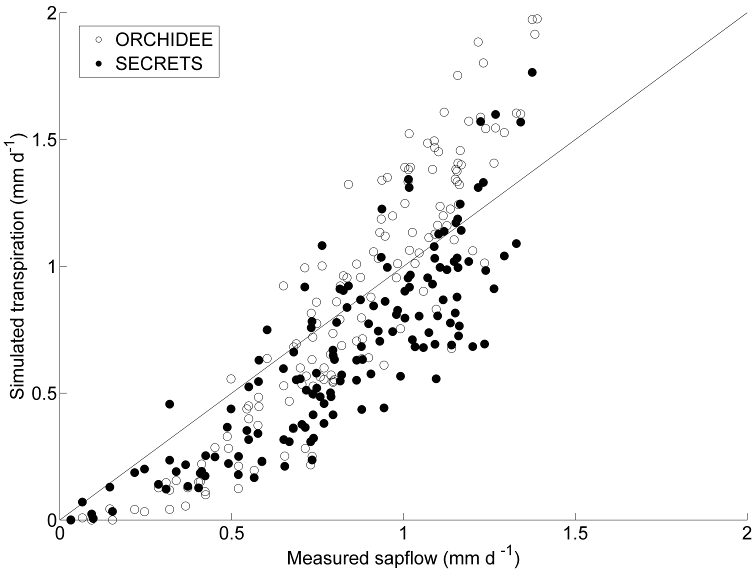

Fig. 4. The relationship between canopy transpiration (mm d^{-1}) simulated by SECRETS (•) and ORCHIDEE (◦) (ordinate) and up-scaled estimates from measured sap flow (abscissa). The solid line depicts the 1:1 relationship.

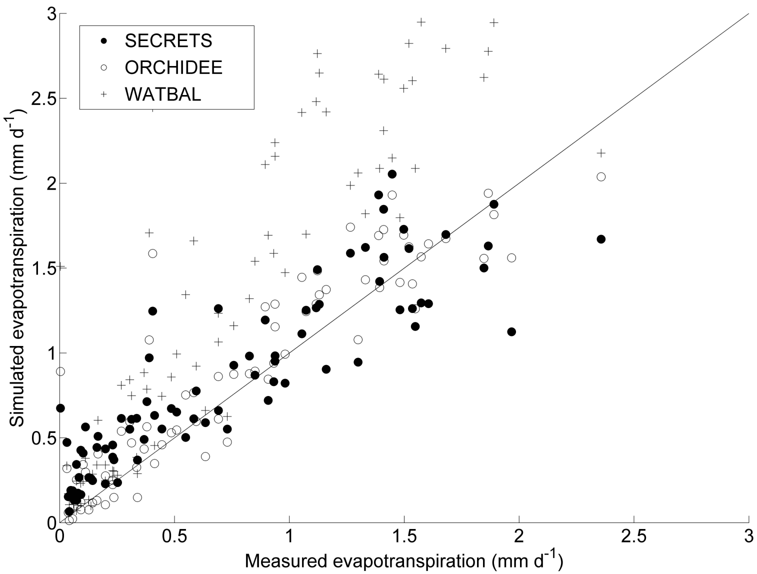

Fig. 5. Mean monthly estimates of latent heat flux measured by eddy covariance (abscissa-mm d^{1}) and model estimates (ordinate) for SECRETS (•), ORCHIDEE (∘) and WATBAL (+). The solid line represents the 1:1 relationship.

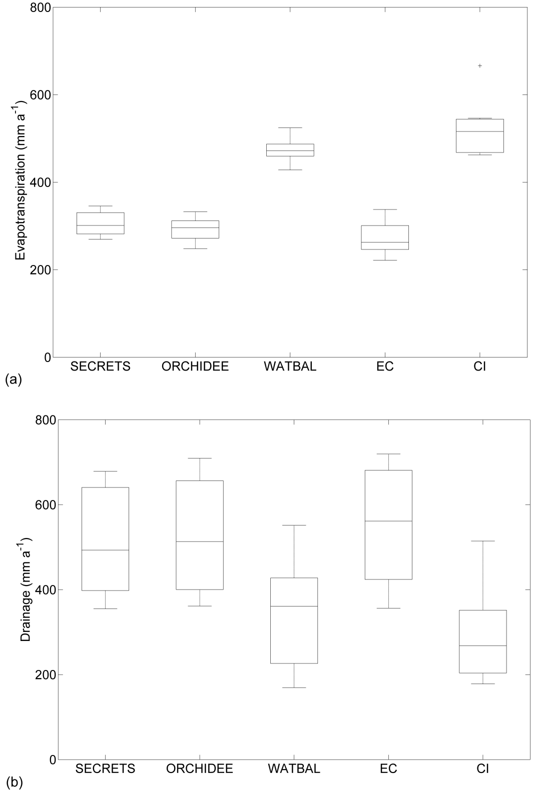

Fig. 6. Box and whisker plots of annual estimates of evapotranspiration **(a)** and drainage **(b)** for the five different approaches used in this study. Data represent the period 1997 through 2008 sans 1998, 1999 and 2003. Box lines depict the lower (25%) quartile, median, and upper (75%) quartile values for each variable. Whiskers, on either end of the box, designate the 95 percentile for each variable. Outliers are represented by the "plus" symbol beyond the ends of the whiskers.

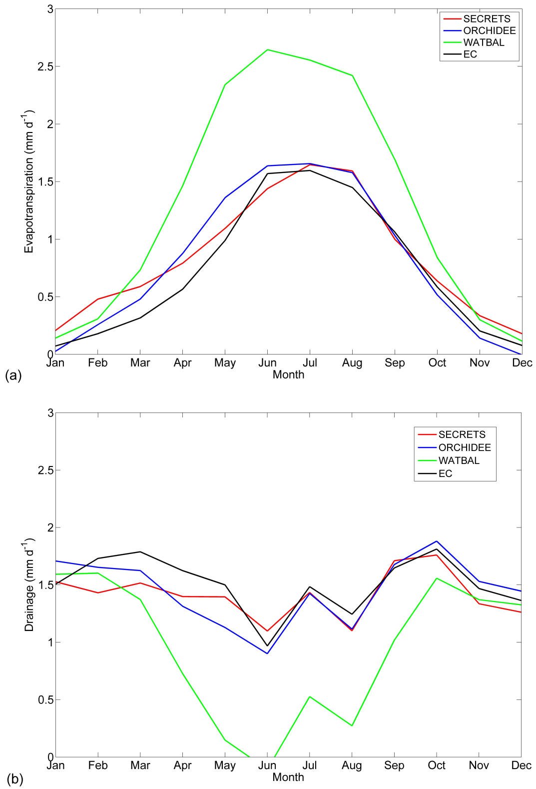

Fig. 7. The seven-year mean seasonal patterns in evapotranspiration (ET) (ordinate) **(a)** and drainage **(b)** expressed as $\text{mm}\,\text{d}^{-1}$ for ORCHIDEE (blue), SECRETS (red), WATBAL (green) and EC (black) approaches. 1998, 1999 and 2003 were excluded because there were no eddy covariance data for these years.

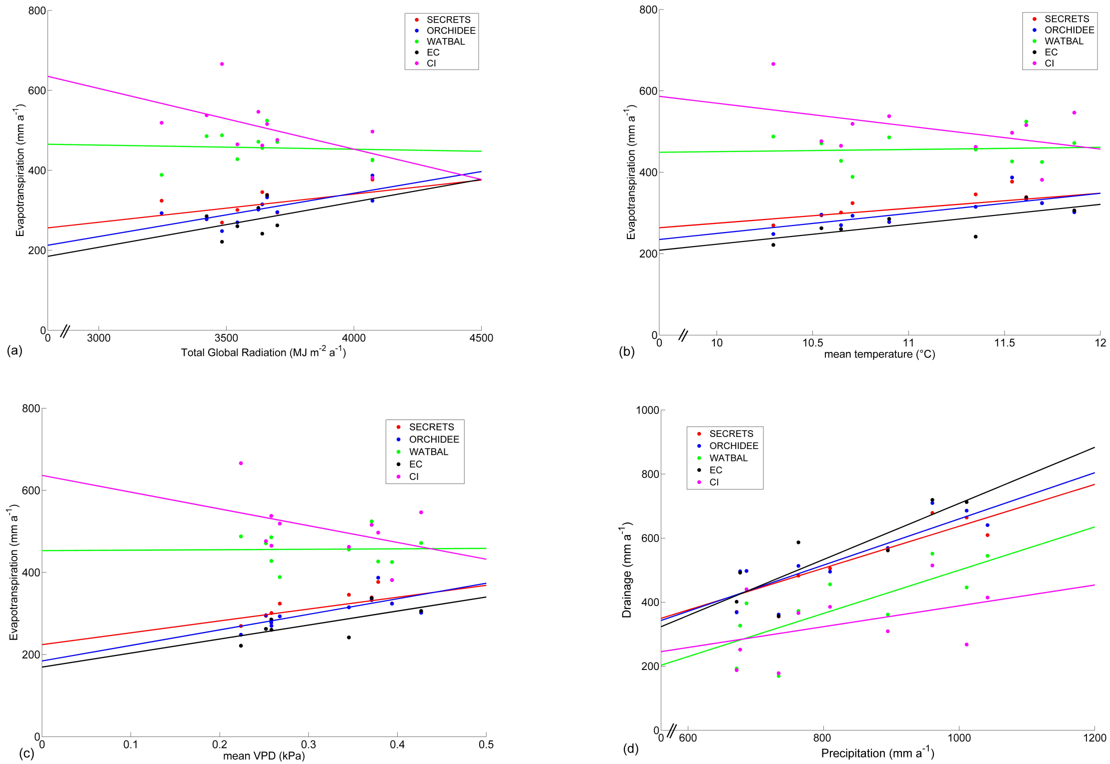

Fig. 8. Linear regression lines for three main drivers of ET for the five different approaches examined in this study. Total global radiation **(a)**, mean annual temperature **(b)** and mean VPD **(c)**. The lower right panel shows **(d)** the relation between annual drainage (ordinate) and precipitation (abscissa).

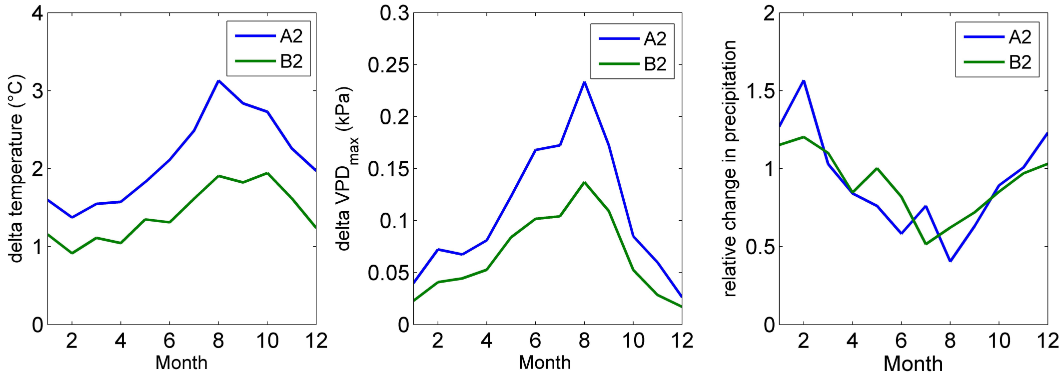

Fig. 9. Mean seasonal absolute temperature increases **(a)** in °C, maximum daily vapour pressure deficit (VPD) **(b)** and relative change in precipitation **(c)** for both IPCC AR4 scenarios: A2 and B2 .

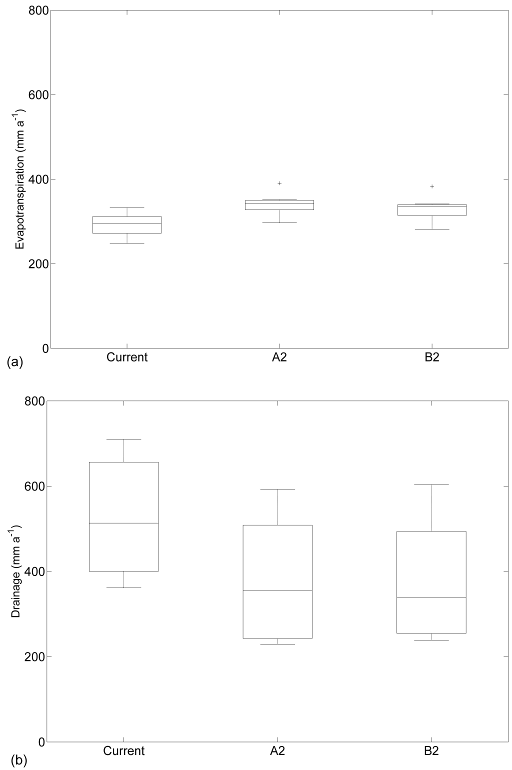

Fig. 10. Box and wisker plots of the potential, future response of evapotranspiration (ET) **(a)** and drainage **(b)** to climatic change as simulated by ORCHIDEE. Each pane shows results for current state, and both IPCC AR4 scenarios: A2 and B2. Box lines designate the lower quartile, median, and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data, the most extreme values within 1.5 times the inter-quartile range from the ends of the box. Outliers are data with values beyond the ends of the whiskers.

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