**TECHNISCHE UNIVERSITÄT DRESDEN**

**Fakultät Forst-, Geo- und Hydrowissenschaften**

# Energy balance of forests with special consideration of advection

(Energiebilanz von Wäldern unter besonderer Berücksichtigung von Advektion)

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vorgelegt von
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**ERKLÄRUNG DER PROMOVENDIN**

Die Übereinstimmung dieses Exemplars mit dem Original der Dissertation zum Thema:

**„Energy balance of forests with special consideration of advection"**

wird hiermit bestätigt.

Dresden, 17.07.2011

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Moderow U, Aubinet M, Feigenwinter C, Kolle O, Lindroth A, Mölder M, Montagnani L, Rebmann C, Bernhofer C (2009) Available energy and energy balance closure at four coniferous sites across Europe. Theor Appl Climatol 98: 397- 412

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# ABSTRACT

The present work was written as a cumulative dissertation based on peer-reviewed papers and is completed by yet unpublished results. The overall objective was to get a deeper insight into the role of the advective fluxes of sensible heat and latent heat in relation to the energy balance and its imbalance at the earth's surface (typically the sum of the turbulent fluxes sensible and latent heat does not match the available energy). Data from two advection experiments at four coniferous sites across Europe served as the basis for the analysis. One was the advection experiment MORE II which took place in Tharandt (Germany) and the other advection experiment ADVEX was conducted at three different sites (Ritten/Renon, Italy; Wetzstein, Germany; Norunda, Sweden).

An inspection of the available energy (AE) that is redistributed to the atmosphere by the sensible heat flux (H) and latent heat flux (LE) showed that the uncertainty of the available energy itself cannot explain the lack of energy balance closure for these four sites. The mean absolute uncertainty of the available energy was largest during midday and ranged from 41 W m$^{-2}$ to 52 W m$^{-2}$ (approx. 12 % of AE). During nighttime, the mean absolute uncertainty was smaller (20 W m$^{-2}$ – 30 W m$^{-2}$) but the relative uncertainty was much larger as AE itself is small. Among the investigated storage terms the heat storage change of the biomass was most important. The energy balance closure was improved for all investigated sites when storage terms were included. In principle, storage terms should not be neglected in energy balance studies.

An investigation of the budget of sensible heat, not only including the vertical advection and the horizontal advection but also the horizontal turbulent flux divergence, was undertaken for the coniferous site at Tharandt. Inclusion of these fluxes resulted in an enlarged mean daily amplitude and suggests an improvement of the energy balance closure, at least during nighttime. The commonly determined budget (vertical turbulent flux plus storage change) was reduced by about 30 % when advective fluxes were included. Results suggest that the horizontal turbulent flux divergence is of minor importance but further studies are needed for an overall evaluation.

First results for the inclusion of the advective fluxes of both sensible heat and latent heat indicate that the lack of energy balance closure is partly reduced but the imbalance still exists.

Advective fluxes of sensible heat were also compared to advective fluxes of $CO_2$. It became apparent that the advective fluxes of sensible heat and $CO_2$ are, on average, of opposite sign during nighttime and both share large scatter. Both budgets (sensible heat and $CO_2$) were considerably changed (although differently for different sites) when advective fluxes were included. Results further suggest that advective fluxes of H can be taken as an indicator concerning the presence and sign of advection of $CO_2$. This points towards a coincident non-turbulent transport of heat and $CO_2$.

However, all investigated advective fluxes are site-specific. They are characterised by a large uncertainty due to uncertainties in the mean vertical velocity (vertical advection) and in the horizontal differences in scalar magnitude (horizontal advection). Obviously, they are influenced by the limitations of the experimental set-up (spatial resolution) and the local characteristics of the individual measurements. An overall evaluation of advective fluxes with respect to their representativeness and magnitude requires further studies.

## ZUSAMMENFASSUNG

Die vorliegende Arbeit wurde als kumulative Dissertation verfasst, die auf begutachteten Publikationen beruht. Sie wird um bisher nicht veröffentlichte Daten zur Advektion latenter Wärme ergänzt. Ziel war es, vor allem die Rolle der advektiven Flüsse von sensibler und latenter Wärme in Bezug auf die Energiebilanz und das Problem der Energiebilanzschließung an der Erdoberfläche näher zu untersuchen. Unter der Energiebilanzschließungslücke wird im Allgemeinen das Phänomen verstanden, dass die Summe der gemessenen turbulenten Flüsse von sensibler und latenter Wärme zumeist nicht der gemessenen verfügbaren Energie entspricht. Als Datengrundlage für die Arbeiten dienten hierzu die Datensätze von zwei Advektionsexperimenten, die an vier verschiedenen Nadelwaldstandorten in Europa stattfanden. Das erste dieser Advektionsexperimente MORE II fand an der Ankerstation Tharandt (Deutschland) statt und das zweite (ADVEX) wurde an drei verschiedenen Standorten durchgeführt (Ritten/Renon, Italien; Wetzstein, Deutschland; Norunda, Schweden).

Eine Untersuchung der verfügbaren Energie (AE), die über den sensiblen Wärmestrom (H) und den latenten Wärmestrom (LE) wieder an die Atmosphäre abgegeben wird, zeigte, dass die in der Bestimmung der verfügbaren Energie liegende Unsicherheit das Problem der Energiebilanzschließungslücke nicht ausreichend erklärt. Die mittlere absolute Unsicherheit der verfügbaren Energie war dabei mittags am größten (41 W m$^{-2}$ – 52 W m$^{-2}$; ca. 12 % der verfügbaren Energie). Nachts war diese kleiner (20 W m$^{-2}$ – 30 W m$^{-2}$). Jedoch waren dann die relativen Unsicherheiten deutlich größer, da die verfügbare Energie nachts klein ist. Von den betrachteten Speichertermen der Energiebilanz erwies sich die Speicheränderung von Wärme in der Biomasse als am wichtigsten. Für die vier untersuchten Standorte verbesserte sich die Energiebilanzschließung, wenn die Speicherterme mit einbezogen wurden. Grundsätzlich sollten alle Speicherterme bei der Bestimmung der Energiebilanz mit beachtet werden.

Für den Nadelwaldstandort Tharandt wurde die Bilanz der sensiblen Wärme unter Beachtung der advektiven Flüsse und der horizontalen turbulenten Flussdivergenz erstellt. Die Einbeziehung der advektiven Flüsse und der horizontalen turbulenten Flussdivergenz führte zu einer Vergrößerung der Amplitude im mittleren Tagesgang

und deutet auf eine Verbesserung der Energiebilanzschließung zumindest nachts hin. Im herkömmlichen Sinne wird die Bilanz für Energie oder Massenflüsse als Summe aus vertikalem turbulenten Fluss und Speicheränderung bestimmt. Die Gesamtsumme dieser Bilanz wurde um 30 % reduziert, wenn die advektiven Flüsse mit einbezogen wurden. Hinsichtlich der horizontalen turbulenten Flussdivergenz kann man noch keine abschließende Einschätzung geben. Die vorliegenden Ergebnisse deuten einen vernachlässigbaren Anteil an der Gesamtbilanz für diesen Term an.

Erste Ergebnisse für die Bestimmung der Energiebilanz von Nadelwäldern unter Beachtung der advektiven Flüsse von sensibler und latenter Wärme zeigen eine teilweise Reduzierung der Energiebilanzschließungslücke, jedoch keine vollständige Schließung der Energiebilanz.

Weiterhin wurden die advektiven Flüsse sensibler Wärme mit denen von $CO_2$ verglichen. Die Bilanzen für den $CO_2$-Fluss als auch für den Fluss sensibler Wärme änderten sich deutlich unter Einbeziehung der advektiven Flüsse, wenn auch unterschiedlich für verschiedene Standorte. Besonders nachts sind die advektiven Flüsse von sensibler Wärme und $CO_2$ im Mittel durch gegensätzliche Vorzeichen gekennzeichnet. Diese Beziehung eröffnet die Möglichkeit, advektive Flüsse von $CO_2$ auf der Basis von advektiven Flüssen sensibler Wärme hinsichtlich ihres Vorhandenseins und ihrer Richtung abzuschätzen. Dies deutet auf einen gleichzeitigen nicht-turbulenten Transport von Wärme und $CO_2$ hin.

Generell ist festzustellen, dass alle untersuchten advektiven Flüsse spezifisch für den jeweiligen Standort und durch eine große Unsicherheit gekennzeichnet sind. Diese ergibt sich zum einen aus der mittleren vertikalen Geschwindigkeit (vertikale Advektion) und zum anderen aus den horizontalen Differenzen (horizontale Advektion) der jeweiligen skalaren Größen. Die betrachteten advektiven Flüsse werden offensichtlich durch Einschränkungen, die sich aus dem experimentellen Aufbau ergeben (z.B. begrenzte räumliche Auflösung), in ähnlicher Weise beeinflusst. Eine abschließende Beurteilung der advektiven Flüsse hinsichtlich ihres Anteils an der Gesamtbilanz und ihrer Repräsentativität erfordert weitere Studien.

# LIST OF SYMBOLS

| Symbols | description | SI unit |
| --- | --- | --- |
| AE | available energy | $W\,m^{-2}$ |
| G | ground heat flux | $W\,m^{-2}$ |
| $G_S$ | heat storage change in the ground between ground surface and depth z | $W\,m^{-2}$ |
| $G_Z$ | ground heat flux below ground surface at depth $z_{HFP}$ | $W\,m^{-2}$ |
| H | sensible heat flux | $W\,m^{-2}$ |
| J | heat storage change | $W\,m^{-2}$ |
| $J_C$ | heat storage change due to photosynthesis | $W\,m^{-2}$ |
| $J_E$ | storage change in latent heat | $W\,m^{-2}$ |
| $J_H$ | storage change in sensible heat | $W\,m^{-2}$ |
| $J_{VEG}$ | heat storage change within biomass | $W\,m^{-2}$ |
| L | side length of control volume | m |
| LE | latent heat flux | $W\,m^{-2}$ |
| $R_{net}$ | net radiation | $W\,m^{-2}$ |
| $S^2$ | sink/source strength | $W\,m^{-2}$; $\mu mol\,m^{-2}\,s^{-1}$ |
| $s^2$ | scalar | $K,\,kg\,m^{-3}$; $\mu mol\,mol^{-1}$ |
| t | time | s |
| u | wind component in the direction of east | $m\,s^{-1}$ |
| $u_*$ | friction velocity | $m\,s^{-1}$ |
| v | wind component in the direction of north | $m\,s^{-1}$ |
| w | vertical wind component | $m\,s^{-1}$ |
| x | distance in direction of east | m |
| y | distance in direction of north | m |
| z | distance in vertical direction (perpendicular to x and y) | m |
| $z_{HFP}$ | measurement height of $G_Z$ below ground surface | m |
| $z_r$ | reference height | m |

[2] SI units are given for the investigated budgets.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ACMB | advection corrected mass balance |
| AE | available energy |
| ASTW | anchor station Tharandter Wald, experimental site in Germany |
| CE-IP | CarboEurope-Integrated project[3] |
| EBR | energy balance ratio |
| $F_{DIV}$ | horizontal turbulent flux divergence |
| $F_{EC}$ | vertical turbulent flux |
| $F_{HA}$ | horizontal advection |
| FLUXNET | global network of micrometeorological sites[4] |
| $F_S$ | storage change |
| $F_{VA}$ | vertical advection |
| NO | Norunda, experimental site in Sweden |
| RE | Ritten/Renon, experimental site in Italy |
| WS | Wetzstein, experimental site in Germany |
| a.g.l. | above ground level |
| a.s.l. | above sea level |

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[3] http://www.bgc-jena.mpg.de/bgc-processes/ceip/ (10.11.2010)
[4] http://daac.ornl.gov/FLUXNET/fluxnet.shtml (10.11.2010)

# 1. INTRODUCTION

The energy balance and connected energy flows together with the water balance are fundamental in the earth-atmosphere system (Oke 1987). They define, together with the physical properties of the system (e.g. altitude, exposition, land use, topography), the climatological conditions we live in. Here, the energy balance[5] of forests shall be in the main focus.

The energy balance is a formulation of the first law of thermodynamics (energy conservation). However, if its components (Eq. 1) are independently measured in the field, a violation of energy conservation is often reported (see section 1.2). This so-called lack (or problem) of energy balance closure and its possible causes is the main issue of the present paper, which tries to add new aspects to the understanding of this phenomenon.

## 1.1 THE ENERGY BALANCE AT THE EARTH'S SURFACE

To introduce the issue of the energy balance, a short overview over its definition is given in the following. The explanations and descriptions given below are based on Oke (1987), Geiger et al. (1995) and Arya (2001) if not otherwise noted.

At first, a flat surface is considered that is horizontal, homogeneous, of infinite horizontal extension and of zero thickness (Fig. 1a). The energy balance at this surface can then be written as follows:

$$R_{net} = H + LE + G \qquad\qquad (1)$$

where $R_{net}$ is net radiation, G ground heat flux. H and LE are the vertical turbulent fluxes of sensible[6] heat and latent[7] heat, respectively. The possible magnitude and

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[5] Heat balance is often used as a synonym for energy balance as heat is one kind of energy.
[6] It is called sensible heat as it could be detected by temperature changes that could be sensed (Oke 1987)
[7] The attribute "latent" is derived from the fact that changes in heat due to changes in the aggregate state of water could not be sensed at a given temperature (Oke 1987).

temporal evolution of the terms of the right hand side of Eq. 1 is determined by the energy input through $R_{net}$ and the physical properties of the respective surface. All terms are given as energy flux densities in W m$^{-2}$. Advective (non-turbulent) exchanges could be neglected as the surface is assumed to be homogeneous, flat and infinite, i.e. there are no gradients of any scalar *s* that could trigger any advective flux. Storage changes could be also neglected since a surface of zero thickness has no mass and can therefore store no energy (Stull 1988).
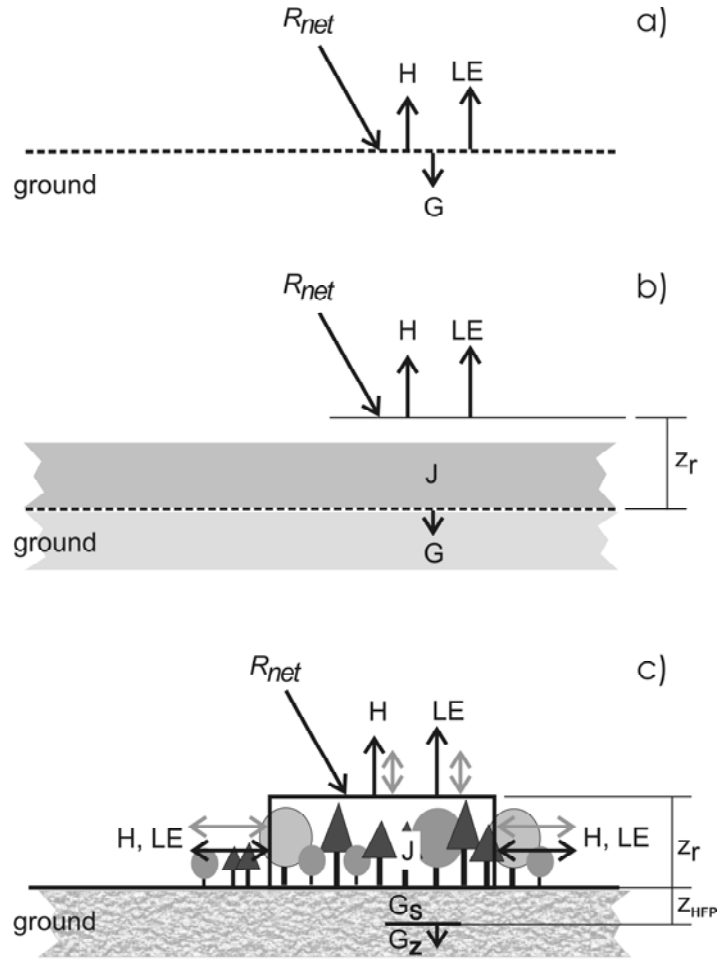


Fig. 1: Scheme for the definition of the energy balance at the earth's surface exemplarily for daytime conditions.
a) for an infinite homogeneous flat surface of zero thickness
b) additional accounting of storage changes within an infinite homogeneous flat layer
c) for the energy balance at the earth's surface including storage changes and vertical as well as horizontal exchanges of H and LE.
In the case of H and LE, black arrows denote turbulent transports and grey arrows denote non-turbulent transports within the air. The rectangular of c) symbolizes the control volume. $z_r$ gives the reference height. Broken lines represent an infinite surface. The storage term $G_S$ must be included when G is not measured directly at the ground surface. $z_{HFP}$ gives the measurement height of $G_Z$ below the ground surface. For further details see section 1.1.1.

However, in most cases, it is not possible to directly measure all terms of Eq. 1 at a surface (e.g. measurement of energy balance terms above a forest). Mostly, H and LE are measured at a suitable height (reference height $z_r$) some metres above ground. It is therefore necessary to account for the storage changes (J) of energy between the earth's surface and the chosen reference height $z_r$ (Fig. 1b). Another problem arises from the assumption of homogeneity, infinity and flatness. These preconditions are rarely, if ever, fulfilled. Physical properties are not uniform and roughness elements are unevenly distributed and of different size. Hence, gradients establish in the horizontal as well as in the vertical direction and roughness elements (e.g. trees) alter the flow. Therefore, advection of energy which is transported in the horizontal directions must be taken into account too (Fig. 1c). This energy is transported by non-turbulent motion and by horizontal turbulent fluxes. Horizontal turbulent flux should be included as turbulence is a chaotic, three dimensional process and hence a change of the vertical turbulent flux also concerns the horizontal turbulent flux. These processes introduce three-dimensionality to the problem of the energy balance. To account for this, a control volume with side length L and height $z_r$ is introduced (Fig. 1c). Storage changes within this volume have to be assessed together with fluxes through the surfaces of control volume.

*Sign convention*

The following sign convention is used: Positive net radiation is directed towards the earth's surface (gain of energy) while a negative net radiation is directed away from the earth's surface (loss of energy). Positive fluxes of sensible heat and latent heat indicate a transport of energy away from the earth's surface into the atmosphere and vice versa. In contrast to this, a positive storage change enlarges the total storage while a negative storage change decreases the total storage[8] within the control volume. A positive ground heat flux indicates that energy is transported from the earth's surface into the ground and negative ground heat flux denotes a transport of energy from the ground to the earth's surface. However, there is a variety of sign conventions throughout the literature as pointed out by Vogt (1995).

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[8]It should be noted that in contrast to the storage changes the magnitude of the total storage is usually unknown.

*1.1.1 Accounting for storage changes*

If storage changes (J) of energy between the earth's surface and the chosen reference height ($z_r$) are taken into account, Eq. 1 alters to:

$$R_{net} - G - J = H + LE \tag{2}$$

Eq. 2 is also rearranged in such a way that the left hand side gives the available energy (AE) that is redistributed to the atmosphere by the vertical turbulent fluxes of latent heat and sensible heat.

J is the sum of different heat storage changes in different parts of the ecosystem of interest due to different processes (Eq. 3). It encompasses storage changes within the canopy air and canopy biomass and can be written as follows (e.g. Bernhofer et al. 2003):

$$J = J_H + J_E + J_{VEG} + J_C \tag{3}$$

where $J_H$ denotes the storage changes of sensible heat (detectable by changes in air temperature over time), $J_E$ the storage change of latent heat (due to processes of condensation and evaporation), $J_{VEG}$ denotes the storage change in biomass (detectable by changes in biomass temperature) and $J_C$ gives the storage change due to photosynthetic activity.

If G is not directly measured at the earth's surface one has to include the storage $G_S$ between the earth's surface and the measurement height $z_{HFP}$ of $G_Z$ below ground surface (see Fuchs 1987). This storage term is commonly treated together with G. The total budget of G would be then defined as follows:

$$G = G_Z + G_S \tag{4}$$

$G_Z$ is the measured heat flux at depth $z_{HFP}$ below ground surface and $G_S$ gives the storage change between depth $z_{HFP}$ and ground surface.

*1.1.2 Accounting for advective exchanges*

Sensible heat and latent heat redistribute the available energy to the atmosphere. For each of these two fluxes a separate budget could be established. Here, the budget equation is derived for any scalar *s*. In the case of sensible heat (latent heat) *s* stands for potential air temperature (absolute humidity). The source or sink strength *S* due to changes in space and time is given by:

$$S(t,x,y,z) = \frac{\partial s}{\partial t} + \frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} + \frac{\partial ws}{\partial z} \tag{5}$$

where *x*, *y* and *z* denotes the three directions in space (east, north and perpendicular to the surface) and *u*, *v*, and *w* are the corresponding wind velocities. *s* denotes the scalar of interest and *t* time. Integrated over the height $z_r$ of the control volume, applying Reynolds averaging and Einstein's summation leads to (Finnigan 1999; Feigenwinter et al. 2004):

$$S(t,x,y,z) = \int_0^{z_r} \left( \frac{\partial \bar{s}}{\partial t} + \frac{\partial (\bar{u}_j \bar{s})}{\partial x_j} + \frac{(\overline{u'_j s'})}{\partial x_j} \right) dz \tag{6}$$

$x_j$ represents the three directions in space and $u_j$ stands for the corresponding wind velocities *u*, *v*, and *w*. An overbar denotes a mean value and primes the deviations from the mean value. Resolving Einstein's summation, taking continuity into account ($\partial \bar{u}/\partial x + \partial \bar{v}/\partial y + \partial \bar{w}/\partial z = 0$) and assuming horizontal homogeneous gradients of the respective scalar *s* ($\partial^2 \bar{s}/\partial x^2 + \partial^2 \bar{s}/\partial y^2 = 0$) gives:

$$S(t,x,y,z) = \int\limits_{0}^{z_r} \frac{\partial \overline{s}}{\partial t}\, dz \quad + \quad \overline{w's'}(z_r) \quad + \quad \int\limits_{0}^{z_r} \overline{w}\frac{\partial \overline{s}}{\partial z}dz +$$

$$\hspace{2.5cm} I \hspace{3cm} II \hspace{2.5cm} III$$

$$\frac{1}{4L^2}\int\limits_{-L}^{+L}\int\limits_{-L}^{+L}\int\limits_{0}^{z_r}\left(\overline{u}(z)\frac{\partial \overline{s}(z)}{\partial x}+\overline{v}(z)\frac{\partial s(z)}{\partial y}\right)dx\,dy\,dz + \hspace{2cm} (7)$$

$$\hspace{4cm} IV$$

$$\frac{1}{4L^2}\int\limits_{-L}^{+L}\int\limits_{-L}^{+L}\int\limits_{0}^{z_r}\left(\frac{\partial\overline{(u's')}}{\partial x}+\frac{\partial\overline{(v's')}}{\partial y}\right)dx\,dy\,dz$$

$$\hspace{4cm} V$$

Term *I* denotes storage change. Term *II* is the vertical turbulent flux at height $z_r$, that could be seen as an integral of all vertical turbulent fluxes below this reference height. In the case of sensible heat (latent heat), term I is equal to $J_H$ ($J_E$) given in Eq. 3 and term *II* is equal to the vertical turbulent flux of H (LE). Term *III* gives the vertical advection and term *IV* the horizontal advection in the direction of *x* and *y*, respectively, and term *V* the divergence of the horizontal turbulent flux. Occasionally, Eq. 7 is termed as advection completed mass balance (ACMB), if the investigated scalar has a mass (Aubinet 2010).

The problem of advection is addressed more in detail in section 1.2.2.

## 1.2 THE PROBLEM OF ENERGY BALANCE CLOSURE

The energy balance is a formulation of the first law of thermodynamics, i.e. energy conservation. Therefore, the right hand side of Eq. 2 must match the left hand side of Eq. 2 and consequently the sum of all terms must equal zero. However, when the different terms of Eq. 2 are independently measured in the field this requirement is seldom fulfilled (typically the sum of the turbulent fluxes H+LE does not match AE). This violation of energy conservation is referred to as lack of energy balance closure. Although the problem of energy balance closure is primarily important for H and LE, it also has implications for other surface fluxes (e.g. carbon dioxide flux) as the atmospheric transport mechanisms are often considered to be similar for different

scalars (e.g. Wilson et al. 2002). However, it should be noted that there is an ongoing discussion about the problem of scalar similarity (e.g. Foken 2008a; Ruppert et al. 2006). Furthermore, the problem of energy balance closure is of main interest concerning calibration and validation of models (e.g. climate models) as data are used for comparison that are likely to be considerably smaller than the true flux (Foken 2008b).

Many studies at a local scale report energy imbalances (e.g. Aubinet et al. 2000; Barr et al. 1994; Bernhofer and Vogt 1999; Blanford et al. 1991; Blanken et al. 1998; Finch and Harding 1998; Jarvis et al. 1997; Kabat et al. 1997; Laubach 1996; Malhi et al. 2002; Oncley et al. 2007; Twine et al. 2000; Wilson et al. 2002). For different FLUXNET sites, including forests, Wilson et al. (2002) give a mean imbalance of 20 %. Table 1 shows an overview of energy imbalances above various surfaces for different experiments.

Tab. 1: Residuals of the energy balance given as percentage of the available energy. Taken from Foken (2008a) and Oncley et al. (2000).

| experiment | residual (%) | surface type | reference |
|---|---|---|---|
| KUREX-88 | 23 | agricultural | Tsvang et al. (1991) |
| FIFE-89 | 10 | steppe | Kanemasu et al. (1992) |
| TARTEX-90 | 33 | agricultural | Foken et al. (1993) |
| VANCOUVER I.-90 | 17 | forest | Oncley et al. (2000) |
| KUREX-91 | 33 | agricultural | Panin et al. (1998) |
| LITFASS-2003 | 20-30 | agricultural | Mauder et al. (2006) |
| EBEX | 10 | agricultural | Oncley et al. (2007) |

However, there are also a few studies – conducted in comparatively homogeneous terrain – that resulted in almost closed energy balances (e.g. Heusinkveld et al. 2004; Mauder et al. 2007). Wilson et al. (2002) formulated hypotheses that may account for the lack of energy balance closure. They are given below (Wilson et al. 2002; p. 225).

1.) sampling errors due to "different measurements source areas for the terms in" Eq. 2

2.) "systematic bias in instrumentation"

3.) neglect of energy sinks

4.) "loss of low and/or high frequency contribution to turbulent" fluxes

5.) neglect of advection

The presented work focuses on hypothesis 3 (neglect of energy sinks) and primarily on hypothesis 5 (neglect of advection). An overview about processes and problems that underlie and or give rise to hypothesis 1, 2 and 4 are given in Foken (2008b) and Foken et al. (2006).

*1.2.1 Neglect of energy sinks*

Daily sums of the different heat storage terms J are often quite small. Mostly, they become insignificant if daily or yearly sums are inspected due to their daily courses (heat gain during day and heat loss during night) and yearly courses. Therefore, these storage changes are frequently neglected. However, it has been shown that the energy balance improves if these storage terms are included (e.g. Aston 1985; Gu et al. 2007; Jacobs et al. 2008; Lindroth et al. 2010; McCaughey et al. 1997; Meyers and Hollinger 2004; Wilson et al. 2002). For an overview of the magnitude and importance of the different storage terms of J please refer to (e.g.) McCaughey (1985), Bernhofer et al. (2003), Oliphant et al. (2004) and Moderow et al. (2009). If the ground heat flux is not measured directly at the earth's surface the storage term $G_S$ should be carefully estimated especially at agricultural sites and sites with bare ground (Cava et al. 2008; Fuchs 1987; Liebethal et al. 2005; Mayocchi and Bristow 1995; Ochsner et al. 2007). For forests, this term could be expected to be small due to smaller shortwave fluxes below the canopy (e.g. Garratt 1992). In the context of forests, $G_S$ has been only (implicitly) addressed in a few studies (e.g. Blanken et al. 1997). There are further, commonly neglected, small terms. Sun et al. (1995) deal with a correction related to the specific heat of moist air in context with the sensible heat flux and Paw U et al. (2000) consider the expansion of air under constant pressure during evaporation in context of the correction after Webb et al. (1980).

*1.2.2 Advection*

Commonly, advection is determined as the transport by the mean wind (Stull 1988) that can occur in the horizontal as well as in the vertical direction and the corresponding fluxes are called advective fluxes or non-turbulent transports. According to Eq. 7 they are calculated by multiplying a gradient of a distinct direction (e.g. $\Delta s/\Delta y$) with the corresponding mean wind (e.g. $\bar{v}$). Advection becomes especially important for conditions of low turbulence (Aubinet et al. 2003, 2005; Marcolla et al. 2005), i.e. for stable atmospheric stratifications that are typical for nighttime conditions. Advection has different reasons. One reason is surface heterogeneity, which leads to differences in scalar magnitude between different points on that surface. These differences result from different responses to mass and energy exchanges as the surface characteristics are not uniform for heterogeneous surfaces. Hence, gradients can establish in the horizontal direction and flows (i.e. advection) develop for compensation (Oke 1987) as equilibrium is always aimed for. Vertical advection is mainly driven by non-zero mean vertical velocities. Non-zero mean vertical velocities occur in context with convection, local circulations and synoptic scale subsidence (Lee 1998; Sun et al. 1998). Drainage flow, a local circulation, could be important in sloping terrain (Aubinet et al. 2003; Feigenwinter et al. 2010a; Lee 1998). Horizontal flow triggers vertical flow (Aubinet et al. 2003) and vice versa and hence both – vertical as well as horizontal advection – have to be considered, as pointed out by Finnigan (1999) and others (Aubinet et al. 2003; Baldocchi et al. 2000; Feigenwinter et al. 2004; Staebler and Fitzjarrald 2004).

As noted by Finnigan (2004), the interest in advection experienced a short "flowering" in relation with observations over pronounced discontinuities some decades ago (e.g. Dyer and Crawford 1965; Rider et al. 1963). For more than 15 years now, advection has been the centre of interest again. This is especially related to the eddy-covariance method that has gained outstanding importance for the estimation of turbulent exchanges of energy and matter between the earth's surface and the atmosphere (Aubinet et al. 2001, 2005; Goulden et al. 1996; Pilegaard et al. 2001; Valentini et al. 1996; Valentini 2003). However, this technique underestimates the total surface flux (Eq. 7) under stable conditions when non-turbulent processes

(i.e. advection and storage) become dominant (Aubinet et al. 2000, 2002, 2005).[9] Therefore, emphasis was put on the assessment of advective fluxes. The initial aim was to obtain more accurate estimates for the Net Ecosystem Exchange of $CO_2$ (e.g. Aubinet et al. 2003, 2005; Baldocchi et al. 2000; Feigenwinter et al. 2004; Lee 1998).

A few studies consider advection in context with the energy balance (e.g. Bernhofer and Vogt 1999; Lee 1998; Lee and Hu 2002; Marcolla et al. 2005; Paw U et al. 2000; Wilson et al. 2002). Bernhofer and Vogt (1999) found no improvement in the energy balance closure when including vertical advection on a daily basis. Lee and Hu (2002) state that vertical advection may contribute to the lack of energy closure. Lee (1998) reports a decrease of the energy balance closure gap when including vertical advection for nighttime data. Paw U et al. (2000) hypothesize that advection may be not negligible for sensible heat flux during nighttime and daytime, whereas advective fluxes of latent heat might be noteworthy during daytime only as the latent heat flux is small during nighttime. A similar conclusion is drawn by Wilson et al. (2002).

## 1.3 OBJECTIVES OF THE WORK

This cumulative dissertation focuses on neglected energy sinks and sources (hypothesis 3) and the neglect of advection (hypothesis 5) for the lack energy balance closure. Moderow et al. (2009) investigated different heat storage terms within four coniferous forests across Europe and address the question of whether the uncertainty of the available energy (Eq. 2) alone could explain the lack of energy balance closure. Secondly, the cumulative dissertation addresses neglected advective fluxes (hypothesis 5). Moderow et al. (2007) present a study where the budget of sensible heat is assessed including non-turbulent advective fluxes and the horizontal turbulent flux divergence (Eq. 7). Thirdly, energy balance estimates are presented which include advective fluxes of sensible heat and latent heat (Moderow et al., unpublished results). Here, the motivation is to explore whether including advective

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[9] For an overview of the problems related to the eddy-covariance technique during nighttime please refer to Aubinet et al. (2008).

fluxes of sensible heat and latent heat improves the energy balance (hypothesis 5). This also concerns the use of the energy balance closure as a quality check for other surface fluxes, such as $CO_2$ (e.g. Aubinet et al. 2000). Fourthly, Moderow et al. (2010) investigate the advective fluxes of sensible heat and $CO_2$ for three forest sites across Europe. Here, the similarity between the advective fluxes of $CO_2$ and sensible heat is explored to answer the question whether the budgets of sensible heat and $CO_2$ are influenced in a similar way. A detailed description of the advective fluxes of $CO_2$ is given in Feigenwinter et al. (2008; Appendix D).

## 2. MATERIAL AND METHODS

The results summarised in section 3 and presented in the Appendices A, B, C and D are based on data of two advection experiments, MORE II and ADVEX. In the following a short overview is given over these two experiments and involved sites.

### 2.1 ADVECTION EXPERIMENT MORE II

MORE II (**M**ore measurements in the **Ore** Mountains) was an advection experiment that took place at the anchor station Tharandter Wald (50°58 N; 13°34 E; Germany) in 2003. It was preceded by the advection experiment MORE I (Feigenwinter et al. 2004) that was conducted at the same site in 2001. The anchor station Tharandter Wald (ASTW) was part of the European carbon and water flux programme CarboEurope-Integrated Project (CE-IP). Its slightly undulating terrain has an average height of 385 m above sea level (a.s.l.) and is mainly covered by Norway spruce (*Picea abies*). The stand has an average height of 29 m (year 2003), a leaf area index of about 5.9 $m^2$ $m^{-2}$ (after a commercial thinning in 2002) and a well-marked trunk space. Mean annual precipitation is 819 mm and the mean annual air temperature is 7.7 °C. The predominant wind direction is south-west. For more detailed information about this site please refer to Grünwald and Bernhofer (2007).

The following condensed overview of the MORE II set-up is restricted to the core issues. During MORE II three additional towers (P1, P2, P3) were erected around the permanent main tower forming a triangle. At these three towers the three wind

components in space (*u, v, w*) were measured by ultrasonic anemometers (METEK, USA-1, Germany; sampling rate 20 Hz) and air temperature by unshielded thermocouples (type E, diameter 75 μm, Campbell Scientific, Logan US; sampling rate 1 Hz). Measurements were taken at two heights above ground level (2.5 m a.g.l. and 30 m a.g.l.). These data served as input for the calculation of horizontal advective fluxes. Figure 2 gives information about the principal set-up. A vertical profile of air temperature measurements at the main tower served as input for the determination of the storage change and vertical advection.
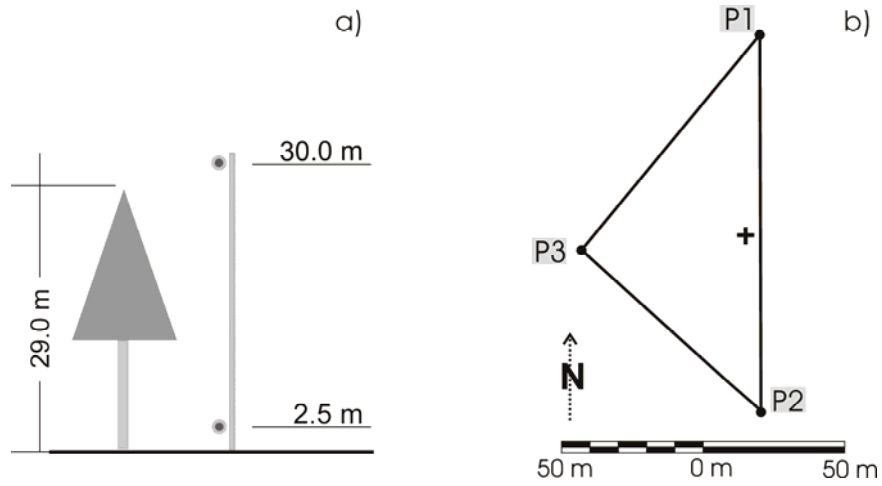


Fig. 2: a) Schematic layout of towers instrumentation P1, P2, P3. Grey circles with dark dot denote measurements of wind components *u, v, w* and of air temperature. b) Scheme of experimental layout of MORE II, black cross denotes the permanent main tower (CE-IP-tower).

For a detailed description of the measurement procedures please refer to Moderow et al. (2007). The advective fluxes based on the MORE II dataset were calculated according to Feigenwinter et al. (2004) and the estimation of the horizontal turbulent flux divergence is outlined in Moderow et al. (2007).

## 2.2 ADVECTION EXPERIMENT ADVEX

ADVEX was an initiative within CE-IP to obtain a deeper insight into advective processes at work. Three basically identical experiments were conducted at three sites across Europe (Ritten/Renon, Italy; Wetzstein, Germany; Norunda, Sweden) one after the other from spring to autumn in 2005 and 2006. All three sites were part of CE-IP and are briefly characterised in the following.

Ritten/Renon (RE) is situated at 1735 m a.s.l. in the Italian Alps (46°25 N, 11°26 E) on a steep slope (inclination 11°, facing south). A local slope wind system exists with south-south-west winds during daytime (upslope) and north-north west winds during nighttime (downslope). Mean annual precipitation is 1010 mm and the mean annual air temperature 4.1 °C. The site is mainly covered (85 %) by Norway Spruce (*Picea abies*) with a height ranging from 20 – 30 m and a leaf area index between 4 to 5.5 $m^2$ $m^{-2}$. A detailed description of the site is given by Marcolla et al. (2005)

Wetzstein (WS) is situated at 782 m a.s.l. (50°27 N, 11°27 E) in Thuringia (Germany) at a ridge. The main wind direction is from south-west. Mean annual precipitation is 840 mm and the mean annual air temperature 5.9 °C. The site is covered by Norway Spruce (*Picea abies*), with an average height of 22 m and leaf area index of 4 $m^2$ $m^{-2}$. A detailed description of the site is given by Rebmann et al. (2010).

Norunda (NO) is a flat site located at 45 m a.s.l. in Sweden (60°05 N, 17°28 E). Only a slight predominance of south-westerly winds exists. Mean annual precipitation is 527 mm and the mean annual air temperature 5.5 °C. The site is covered by Norway Spruce (*Picea abies*) and Scots Pine (*Pinus sylvestris*), with an average height of 29 m and the leaf area index ranges between 3 and 6 $m^2$ $m^{-2}$. A detailed description of the site is given by Lundin et al. (1999).

The ADVEX set-up and measurement scheme is described in detail in Feigenwinter et al. (2008). Here, only a condensed overview is given. During the ADVEX campaigns four additional towers (A, B, C, D) were erected forming a quadrangle (Fig. 3) with the permanent main tower in the middle. At these additional towers measurements were taken at four heights. These measurements comprised measurements of the three wind components in space, air temperature, $CO_2$ and water vapour. Wind components were measured by ultrasonic anemometers 81000V (R.M. Young Meteorological Instruments, US; sampling rate 10 Hz) and at tower C instruments of type R3 (Gill Instruments Ltd., UK; sampling rate 20 Hz) were also employed. Air temperature was measured by unshielded thermocouples (type E, diameter 75 μm, Campbell Scientific, Logan US; sampling rate 0.5 Hz). $CO_2$ and water vapour were measured by infra-red gas analysers (Li6262/7000, Li-Cor, Lincoln, US) and each measurement point at the towers was probed every 160 s.

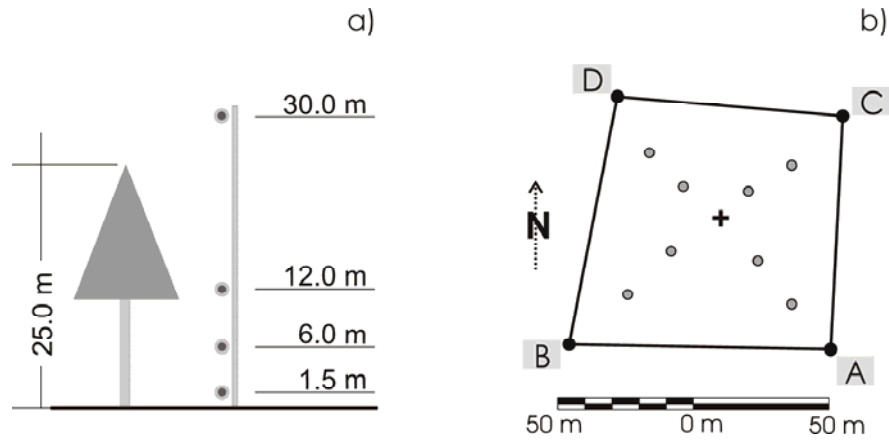The advective fluxes based on the ADVEX dataset were calculated according to Feigenwinter et al. (2008).



Fig. 3: a) Schematic layout of towers instrumentation A, B, C, D. Grey circles with dark dot denote measurements of wind components *u, v, w*, air temperature, $CO_2$ and water vapour. b) Scheme of experimental layout of ADVEX (example of Norunda), black cross denotes the permanent main tower (CE-IP-tower), grey dots denote measurements in between towers.

## 3. SUMMARY AND MAJOR FINDINGS

In this section the most important results and findings of the individual papers are brought together.

If one looks at Eq. 2 then it is apparent that different terms contribute to the energy balance and each of these terms can be determined in a different way and have their importance and of course each is error prone to some degree. The available energy is given by the left hand side of Eq. 2 and is redistributed to the atmosphere by the sensible heat flux and the latent heat flux. An unclosed energy balance can be caused by several reasons (see section 1.2). Before evaluating the role of sensible heat flux and latent heat flux in this context it is a precondition to assess the available energy accurately. A careful estimation and inspection of the available energy and the involved uncertainties was done for four coniferous sites across Europe (Moderow et al. 2009; Appendix A) on the basis of the MORE II and ADVEX dataset. It was shown that the often found imbalance of the energy balance could not be explained by the uncertainties in the available energy (AE) alone. The largest absolute uncertainties in AE were found during midday and ranged from 41 W m$^{-2}$ to 52 W m$^{-2}$ corresponding to approximately 12 % of the available energy. The absolute

uncertainties were smaller ($20 - 30$ W m$^{-2}$) during nighttime. However, this resulted in large relative uncertainties as the available energy itself is small during nighttime.

The inclusion of the different storage terms improved the energy balance as reported in previous studies (e.g. Aston 1985; Gu et al. 2007; McCaughey et al. 1997; Meyers and Hollinger 2004; Wilson et al. 2002). For the four investigated sites, the slope of linear regression between the available energy and the sum of $(H + LE)$ increased when storage terms were included, whereas the offset of the linear regression decreased. Of the different storage terms, the heat storage of the biomass was most important. This suggests that this term should deserve more attention in energy balance studies, which is in accordance with recently published results (e.g. Haverd et al. 2007; Lindroth et al. 2010). Although the energy balance was improved by inclusion of the storage terms, up to 30 % of the energy balance closure gap still remained unexplained. Therefore, other causes such as advection must be taken into consideration.

Advection is the transport by the mean wind and concerns the budgets of sensible heat and latent heat, i.e. the right hand side of Eq. 2. Commonly, the budget of sensible heat and latent heat is determined as the sum of the vertical turbulent flux ($F_{EC}$) and the storage change ($F_S$) beneath the reference height $z_r$. To account for vertical and horizontal advective transports and horizontal turbulent flux divergence ($F_{DIV}$), one must extend the budgets of sensible heat and latent heat according to Eq. 7. Moderow et al. (2007; Appendix B) investigated the budget of sensible heat including these advective transports and the horizontal turbulent flux divergence on the basis of the MORE II dataset. Inclusion of advective fluxes into the sensible heat budget reduced the commonly determined budget ($F_{EC}+F_S$) by about 30 %. If, in addition to this, the horizontal turbulent flux divergence was also taken into account, this sum ($F_{EC}+F_S+F_{HA}+F_{VA}$) was reduced by about 5-10 % again. The daily amplitude of sensible heat was enlarged (i.e. larger absolute fluxes during night and day) if advective fluxes as well as the horizontal turbulent flux divergence were taken into account. In relation to the available energy, the horizontal advection was most important during the night while the horizontal flux divergence was rather unimportant over the whole day. These results suggest that inclusion of advective fluxes would decrease the lack of energy balance closure, at least during nighttime.

However, on a daily basis inclusion of advective fluxes does not necessarily reduce the lack of energy balance closure. In contrast to this, horizontal turbulent flux divergence would slightly reduce this deficit over the day.

It should be noted that these results are merely based on the extended budget of sensible heat and an overall evaluation of the advective fluxes concerning the energy balance closure could only be done if the advective fluxes of latent heat are considered too.

How the energy balance would change when advective fluxes were included was explored for the three ADVEX sites. This was done for the experimental periods as denoted in Moderow et al. (2009) where the determination of the vertical turbulent fluxes of H and LE used here is also outlined. It should be noted that these fluxes were taken some meters above the uppermost ADVEX-level (see section 2.2) Furthermore special synoptic conditions ("southerlies", "tramontana", see Feigenwinter et al. 2008) were excluded from analysis in the case of RE as well as across ridge flows in the case of WS (see Feigenwinter et al. 2008 and Zeri et al. 2010).

First, the mean daily course for the latent heat flux was calculated including vertical and horizontal advective fluxes (Fig. 4). Figure 4 shows that advection of latent heat is probably more important during nighttime than during daytime. This is in contradiction to Paw U et al. (2000) who hypothesized that advection of latent heat is negligible during nighttime as the vertical turbulent latent heat flux is close to zero.

A comparison with the mean daily course of sensible heat reveals consistent behaviour. On average, inclusion of advective fluxes increased the sensible heat flux (larger negative fluxes at night) whereas positive values for the latent heat flux were found at RE and WS during nighttime. This suggests that energy added by the sensible heat flux is used for evaporation. A reverse behaviour was found at NO for nighttime. This is consistent with the (on average) opposite sign of the advective fluxes of $CO_2$ at NO compared to RE and WS (Feigenwinter et al. 2008; Appendix D). The energy balance residuals ($R_{net} - G - J - H - LE$) were investigated in relation to $R_{net}$ and friction velocity ($u_*$) for nighttime conditions. Residuals changed for all sites but scatter was increased when advective fluxes were included (Fig. 5).
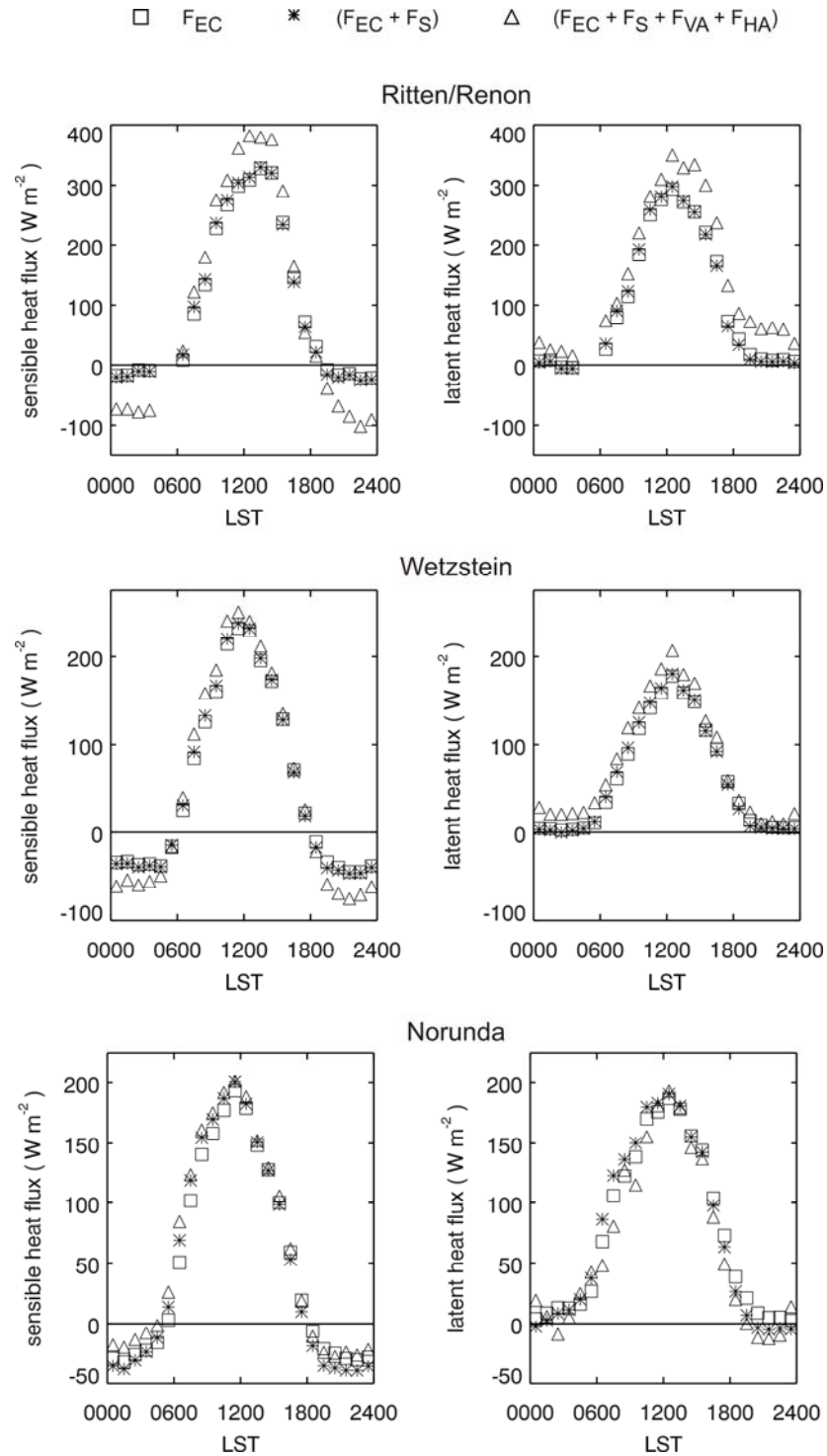
Fig. 4: Mean daily courses of sensible (left column) and latent (right column) heat flux budgets with and without $F_S$ and $F_{VA}$ and $F_{HA}$, respectively. LST denotes local standard time. One hour averages are given averaged over a period of 81 (69, 74) days for RE (WS, NO). Rainy periods and periods with relative humidity > 95 % were excluded. Presentation of scatter was omitted for clarity.

Inclusion of advective fluxes reduced the residuals at RE and WS, especially for large negative $R_{net}$. However, the residuals did not vanish. Similar behaviour was found in relation to $u_*$ (not shown). Reduced residuals were found below a threshold of approximately $u_* = 0.4$ m s$^{-1}$ for RE and WS. No clear behaviour could be found in relation to $R_{net}$ and $u_*$ for NO during nighttime.
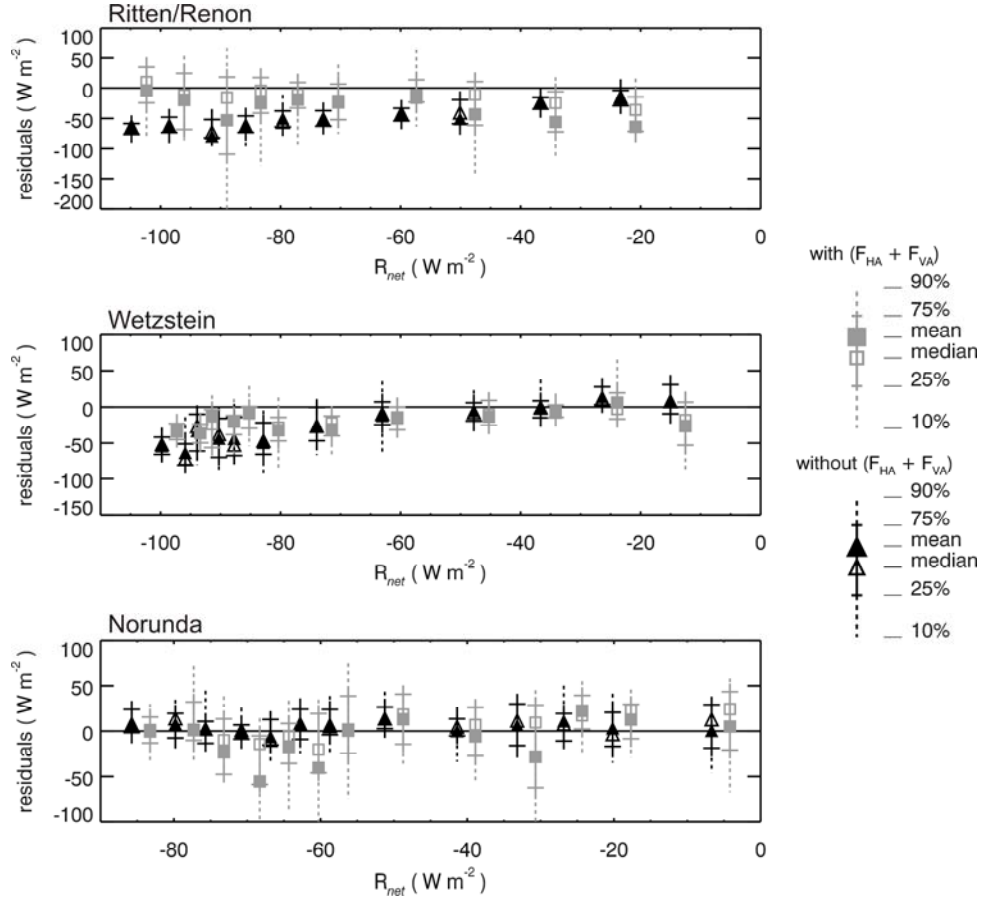


Fig. 5: Energy balance residuals ($R_{net} - G - J - H - LE$) in relation to $R_{net}$ during nighttime based on hourly data. Each bin contains 25 values. Residuals were investigated for a period of 81 (69, 74) days for RE (WS, NO). Rainy periods and periods with relative humidity > 95 % were excluded.

Table 2 shows a comparison of the mean values for the available energy and the sum of sensible and latent heat flux with and without advective fluxes. These are separately given for night ($R_{net} < 0$ W m$^{-2}$), day ($R_{net} > 0$ W m$^{-2}$) and for the whole day. The given energy balance ratio (EBR) was calculated as follows,

$$EBR = \frac{\sum(H + LE)}{\sum(AE)} \qquad (8)$$

The results change differently for each site when advective fluxes are included. In the case of RE and WS, the energy balance is improved for nighttime conditions and the EBR increases. However, nighttime fluxes at NO may be to scattered for any discussion on the basis of the EBR. The interpretation of the nocturnal advective energy fluxes might be similarly critical as for the advective fluxes of $CO_2$ as reported by Feigenwinter et al. (2010b). During daytime the already existing surplus of the energy fluxes is increased at RE resulting in an even larger EBR when advective fluxes are included, whereas, in the case of WS (NO), the energy balance closure is considerably improved. This stresses that advective fluxes are not only

Tab. 2: Mean values of available energy and the sum of sensible heat and latent heat flux without and with advective fluxes based on hourly data. EBR denotes energy balance ratio. Rainy periods and periods with relative humidity > 95 % were excluded.

| | | without advective fluxes | | with advective fluxes | |
| --- | --- | --- | --- | --- | --- |
| | AE<br>W m$^{-2}$ | H + LE<br>W m$^{-2}$ | EBR<br>- | H + LE<br>W m$^{-2}$ | EBR<br>- |
| Ritten/Renon | | | | | |
| day | 354 | 401 | 1.13 | 486 | 1.37 |
| night | -50 | -2 | 0.04 | -16 | 0.32 |
| day and night | 180 | 227 | 1.26 | 270 | 1.50 |
| Wetzstein | | | | | |
| day | 309 | 228 | 0.74 | 257 | 0.83 |
| night | -53 | -30 | 0.56 | -34 | 0.64 |
| day and night | 154 | 118 | 0.77 | 132 | 0.86 |
| Norunda | | | | | |
| day | 225 | 247 | 1.10 | 239 | 1.06 |
| night | -9 | -14 | 1.54 | 0 | 0.05 |
| day and night | 143 | 156 | 1.09 | 156 | 1.09 |

important during nighttime. If one considers the whole day then the energy balance is changed dramatically at RE (now showing a puzzling over-closure of 50 %!) and is virtually not changed at NO when advective fluxes are included. This in agreement

with the common assumption, that a sloped site (due to the local wind system) would be influenced by advection, whereas, in the case of an (ideal) flat site, the influence of advection would be negligible. However, this does not mean that there are no advective fluxes at an (ideal) flat site. Considering the EBR of 1.5, a second look at the AE and the turbulent fluxes in RE might be useful. E.g., a careful evaluation of effects of rotation on turbulent fluxes or slope and aspect on $R_{net}$ is a possible next step to address the over-closure at the site.

The results for the inclusion of advective fluxes in the energy balance are multifaceted. They support the hypothesis that neglect of advection may lead to inaccurate energy balance estimates but inclusion of advective fluxes does not necessarily result in a closed energy balance. Further studies over longer periods and also for non-forested sites may help to enhance the understanding.

Frequently, the energy balance closure is also taken as a quality check for other surface fluxes (e.g. $CO_2$) that are assessed by the same method (i.e. eddy-covariance method, e.g. Aubinet et al. 2000). It is assumed that if the vertical turbulent energy fluxes are not captured very well, it is likely that other vertical turbulent fluxes (e.g. $CO_2$) are missed too (e.g. Laubach and Teichmann 1999; Twine et al. 2000). This is based on similarity assumptions concerning the turbulent scalar transport (see, e.g. Oke 1987, Stull 1988). It is therefore interesting to investigate whether energy budgets (e.g. sensible heat flux) and mass budgets (e.g. $CO_2$) are influenced by advective fluxes in a similar way. Moderow et al. (2010; Appendix C) compared advective fluxes of sensible heat and $CO_2$ for three coniferous sites across Europe on the basis of the ADVEX-dataset (Feigenwinter et al. 2008; Appendix D). It turned out that the advective fluxes of both investigated fluxes (sensible heat and $CO_2$) were, on average, of opposite sign especially during nighttime. As this was found for the horizontal advective fluxes as well as the vertical advective fluxes this suggests that the advective transports of both fluxes evolve in an opposite manner, at least during nighttime. Results further suggest that those opposite advective fluxes are favoured by distinct site characteristics such as the local slope wind system at Ritten/Renon.

The contrasting behaviour in sign gave rise to the idea of using advective fluxes of sensible heat as a proxy for the advective fluxes of $CO_2$. Thus far, results suggest that

the advective fluxes of sensible heat might be taken as an indicator concerning the sign and presence of $CO_2$ advection. However, a quantitative approximation of the advective fluxes of $CO_2$ on the same assumption remains to be further examined. Inclusion of the advective fluxes into the budgets caused a considerable change of the budgets for sensible heat as well as for $CO_2$. Over the whole day, the budget of $CO_2$ might be generally more affected by advection than the budget of sensible heat (Moderow et al. 2010). Mean daily amplitudes of both fluxes were differently changed for the three inspected sites (see Fig. 4 in the case of sensible heat). A decrease in the mean daily amplitude was found in the case of NO. At WS and RE mean daily amplitudes of both fluxes (sensible heat and $CO_2$) were increased. This would enlarge the total $CO_2$ flux (respiratory flux) and total sensible heat flux during nighttime. Concerning the energy balance, this suggests that an inclusion of the advective fluxes might improve the energy balance, at least during nighttime in the case of WS and RE. However, this does not necessarily imply that the energy balance closure improves on a daily basis. Similar results were reported by Moderow et al. (2007) for the coniferous site in Germany.

The investigation of the different advective fluxes (sensible heat and $CO_2$) revealed that both are similarly influenced. Large horizontal advective fluxes were found for $CO_2$ as well as for sensible heat. Especially in the case of $CO_2$, their representativeness and magnitude is not yet clarified and they are often not in accordance with $CO_2$ flux estimates based on alternative methods such as chamber measurements (Aubinet et al. 2010).

Although the energy balance residuals partly decreased when advective fluxes were included they still persist. Two main complexes of problems can be identified which contribute to this result.

The *first* one encompasses problems involved in the determination of advective fluxes and the second one is related to the energy balance approach itself and neglected fluxes. The measurement and determination of advective fluxes is a challenging task. Here, the determination of the mean vertical velocity in the case of the vertical advection and the assessment of representative differences in scalar magnitude (gradients) at a reliable level in the case of horizontal advection are of main interest (Heinesch et al. 2007). In general, the mean vertical velocity is quite

small. Its magnitude often equals the magnitude of the accuracy of the ultrasonic anemometer, or is even smaller. Additionally, it tends to scatter around zero. Furthermore, depending on the chosen calculation method it can change in sign and magnitude. It can be stated that the determination of mean vertical velocity is still an unsolved problem. Numerous publications address this problem and investigate it more in detail (e.g. Dellwik et al. 2010; Heinesch et al. 2007; Lee 1998; Mammarella et al. 2007; Sun 2007; Vickers and Mahrt 2006). Aubinet et al. (2010) investigate the effect of several methods for determination of the mean vertical velocity for the ADVEX dataset. For a detailed discussion of the uncertainties of the advective flux estimates please refer to Aubinet et al. (2010) and Moderow et al. (2010) in the case of the ADVEX dataset and in the case of MORE II please refer to Moderow et al. (2007). Concerning the horizontal advection, determined differences in scalar magnitude (gradients) are often very small. Like the mean vertical velocity, their magnitude could also be within the uncertainty limits of the instruments. Furthermore, it is not clarified in every case how representative the determined gradients for the exchange of the inspected surface are. Mauder et al. (2010) and Thomas (2010) explicitly question the often (implicitly) applied assumption of linear scalar gradients. One should keep in mind that advection is very likely a scale overlapping process. The gradients are more locally influenced but the flow field is often a result of processes at larger scales (e.g. Feigenwinter et al. 2008).

The *second* complex deals with the energy balance approach itself and neglected fluxes. The total energy balance was addressed, including advective fluxes of sensible heat and latent heat, but the horizontal turbulent flux divergence was still neglected. This term was only inspected in relation to sensible heat and was not included in the total energy balance budget. Consequently, according to Eq. 7, the budgets for sensible heat and latent heat are still incomplete and hence the energy balance too. Therefore, the inclusion of the horizontal turbulent flux divergence in the energy balance of both sensible heat and latent heat still remains a challenge. Leuning et al. (2008) stress that the advantages of the micrometeorological balance approach as denoted by Eq. 7 may not counterbalance the errors and uncertainties of the necessary measurements. This statement is supported by Aubinet et al. (2010) who principally question its applicability.

# 4. CONCLUSIONS AND OUTLOOK

The calculation of the available energy for four coniferous sites across Europe showed, in agreement with other studies, that storage terms should be not neglected within energy balance studies and that all storage terms should be carefully estimated. Furthermore, it could be shown that the uncertainty of the available energy itself could not explain the lack of energy balance closure and other possible causes, such as advection, have to be explored. The budgets of sensible heat and latent heat are changed if advective fluxes are included, and the energy balance is influenced by advective processes. Inclusion of advective fluxes in the energy balance partly reduced the imbalance. This suggests that an improvement of the energy balance closure by including advective fluxes might be also possible at other sites. Concerning, the horizontal turbulent flux divergence, the gained insights indicate that this flux term might be of minor importance in the case of sensible heat. However, its overall importance also for other energy and mass fluxes is still difficult to evaluate and requires further investigation. A comparison of advective fluxes of sensible heat and $CO_2$ showed that similarities exist between these fluxes. Results suggest that the budget of $CO_2$ might be generally more altered by advective fluxes than the budget of sensible heat. It turned out that advective fluxes are highly site-specific and the presented findings should be applied to other sites with caution. One should note that the assessment of the advective fluxes in their present form bears considerable uncertainty that is difficult to determine and the representativeness and magnitude of direct advection measurements are not yet well understood. The representativeness of advective fluxes is related to the experimental set-up as this is often a compromise between desired set-up and possible set-up (e.g. spatial resolution).

Despite inclusion of advective fluxes, energy balance imbalances persist. This can be related to problems associated with advective fluxes (i.e. representativeness and involved large uncertainties) and problems related to the energy balance approach (i.e. unaccounted fluxes). Here, new techniques or improvement of existing techniques might be a promising step. One option could be to consider the energy balance imbalances with respect to the surface heterogeneity, as proposed by Panin et al. (1998) and as noted by Foken et al. (2010). Another option is the investigation of

quasi stationary circulations (Mauder et al. 2008) and their implications for the energy balance. Therefore, the development of new techniques and existing techniques to assess the total mass or energy surface flux should be a core issue of further research, as stated by e.g., Mauder et al. (2010) and Nakamura and Mahrt (2006). In this light, the statement of Rider (1963; p. 507) that "There is scope for further theoretical and experimental work on this matter." is still valid today.

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Fig. 1: Scheme for the definition of the energy balance at the earth's surface for daytime conditions.

a) for an infinite homogeneous flat surface of zero thickness

b) additional accounting of storage changes within an infinite homogeneous flat layer

c) for the energy balance at the earth's surface including storage changes and vertical as well as horizontal exchanges of H and LE.

In the case of H and LE, black arrows denote turbulent transports and grey arrows denote non-turbulent transports within the air. The rectangular of c) symbolizes the control volume. $z_r$ gives the reference height. Broken lines represent an infinite surface. The storage term $G_S$ must be included when G is not measured directly at the ground surface. $z_{HFP}$ gives the measurement height of $G_Z$ below the ground surface. For further details see section 1.1.1.

Fig. 2: a) Schematic layout of towers instrumentation P1, P2, P3. Grey circles with dark dot denote measurements of wind components $u, v, w$ and of air temperature. b) Scheme of experimental layout of MORE II, black cross denotes the permanent main tower (CE-IP-tower).

Fig. 3: a) Schematic layout of towers instrumentation A, B, C, D. Grey circles with dark dot denote measurements of wind components $u, v, w$, air temperature, $CO_2$ and water vapour. b) Scheme of experimental layout of ADVEX (example of Norunda), black cross denotes the permanent main tower (CE-IP-tower), grey dots denote measurements in between towers.

Fig. 4: Mean daily courses of sensible (left column) and latent heat flux budgets (right column) with and without $F_S$ and $F_{VA}$ and $F_{HA}$, respectively. LST denotes local standard time. One hour averages are given averaged over a period of 81 (69, 74) days for RE (WS, NO). Rainy periods and periods with relative humidity > 95 % were excluded. Presentation of scatter was omitted for clarity.

Fig. 5: Energy balance residuals ($R_{net} - G - J - H - LE$) in relation to $R_{net}$ during nighttime based on hourly data. Each bin contains 25 values. Residuals were

investigated for a period of 81 (69, 74) days for RE (WS, NO). Rainy periods and periods with relative humidity > 95 % were excluded.

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# APPENDIX A – AVAILABLE ENERGY AND ENERGY BALANCE CLOSURE AT FOUR CONIFEROUS SITES ACROSS EUROPE[11]

Moderow U[a], Aubinet M[b], Feigenwinter C[b,f], Kolle O[c], Lindroth A[d], Mölder M[d], Montagnani L[e], Rebmann C[c], Bernhofer C[a]

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**Abstract** The available energy (AE), driving the turbulent fluxes of sensible heat and latent heat at the earth surface, was estimated at four partly complex coniferous forest sites across Europe (Tharandt, Germany; Ritten/Renon, Italy; Wetzstein, Germany; Norunda, Sweden). Existing data of net radiation were used as well as storage change rates calculated from temperature and humidity measurements to finally calculate the AE of all forest sites with uncertainty bounds. Data of the advection experiments MORE II (Tharandt) and ADVEX (Renon, Wetzstein, Norunda) served as the main basis. On-site data for referencing and cross-checking of the available energy were limited. Applied cross checks for net radiation (modelling, referencing to nearby stations and ratio of net radiation to global radiation) did not reveal relevant uncertainties. Heat storage of sensible heat $J_H$, latent heat $J_E$, heat storage of biomass $J_{veg}$ and heat storage due to photosynthesis $J_C$ were of minor importance during day but of some importance during night, where $J_{veg}$ turned out to be the most important one. Comparisons of calculated storage terms ($J_E$, $J_H$) at different towers of one site showed good agreement indicating that storage change calculated at a single point is representative for the whole canopy at sites with moderate heterogeneity. The uncertainty in AE was assessed on the basis of

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literature values and the results of the applied cross checks for net radiation. The absolute mean uncertainty of AE was estimated to be between 41 and 52 W m$^{-2}$ (10–11 W m$^{-2}$ for the sum of the storage terms J and soil heat flux G) during mid-day (approximately 12% of AE). At night, the absolute mean uncertainty of AE varied from 20 to about 30 W m$^{-2}$ (approximately 6 W m$^{-2}$ for J plus G) resulting in large relative uncertainties as AE itself is small. An inspection of the energy balance showed an improvement of closure when storage terms were included and that the imbalance cannot be attributed to the uncertainties in AE alone.

# APPENDIX B – ESTIMATING THE COMPONENTS OF THE SENSIBLE HEAT BUDGET OF A TALL FOREST CANOPY IN COMPLEX TERRAIN[12]

Moderow U[a], Feigenwinter C[b], Bernhofer C[a]

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**Abstract** Ultrasonic wind measurements, sonic temperature and air temperature data at two heights in the advection experiment MORE II were used to establish a complete budget of sensible heat including vertical advection, horizontal advection and horizontal turbulent flux divergence. MORE II took place at the long-term Carbo-Europe IP site in Tharandt, Germany. During the growing period of 2003 three additional towers were established to measure all relevant parameters for an estimation of advective fluxes, primarily of $CO_2$. Additionally, in relation to other advection experiments, a calculation of the horizontal turbulent flux divergence is proposed and the relation of this flux to atmospheric stability and friction velocity is discussed. In order to obtain a complete budget, different scaling heights for horizontal advection and horizontal turbulent flux divergence are tested. It is shown that neglecting advective fluxes may lead to incorrect results. If advective fluxes are taken into account, the sensible heat budget based upon vertical turbulent flux and storage change only, is reduced by approximately 30%. Additional consideration of horizontal turbulent flux divergence would in turn add 5–10% to this sum (i.e., the sum of vertical turbulent flux plus storage change plus horizontal and vertical advection). In comparison with available energy horizontal advection is important at night whilst horizontal turbulent flux divergence is rather insignificant. Obviously, advective fluxes typically improve poor nighttime energy budget closure and might change ecosystem respiration fluxes considerably.

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# APPENDIX C – NON-TURBULENT FLUXES OF CARBON DIOXIDE AND SENSIBLE HEAT – A COMPARISON OF THREE FORESTED SITES[13]

Moderow U[a], Feigenwinter C[b], Bernhofer C[a]

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**Abstract** The advection initiative ADVEX within CarboEurope-IP conducted advection experiments at three European coniferous sites in 2005 and 2006. All experiments shared the same geometry and instrumentation. Data of the ADVEX experiments were used to calculate advective fluxes of carbon dioxide and sensible heat using exactly the same method. However, the advective flux of sensible heat can be assessed more easily than the carbon dioxide flux with its associated complex measurements of gas concentrations. We explored the possibility to use advective fluxes of sensible heat as a proxy for the corresponding flux of carbon dioxide despite somewhat differing sinks and sources. On average, advective fluxes of sensible heat were of opposite sign in relation to the advective fluxes of carbon dioxide for the three investigated sites, especially during nighttime. Therefore, the respective gradients were of opposite sign, on average, for vertical and (to a lesser extent) horizontal direction. This is not as obvious for horizontal direction as for the vertical direction. A scheme is presented to explain the correlation of the respective gradients for different conditions. Based on the gained insights and regression statistics, two simple empirical models were tested to derive advective fluxes of carbon dioxide from advective fluxes of sensible heat. Our results suggest that the advective flux of sensible heat could be taken as an indicator concerning the presence and sign of carbon dioxide advection. However, the suitability of advective fluxes of sensible heat as a quantitative proxy for advective fluxes of carbon dioxide is more

problematic because the representativeness including the magnitude of advection derived from advection measurements is not yet clarified. An inspection of the budget of sensible heat and carbon dioxide revealed considerable changes by advection. The results indicate that the budget of carbon dioxide might be generally more affected by the investigated non-turbulent advective fluxes than the budget of sensible heat.

# APPENDIX D – COMPARISON OF HORIZONTAL AND VERTICAL ADVECTIVE $CO_2$ FLUXES AT THREE FOREST SITES[14]

Feigenwinter C[a,g], Bernhofer C[b], Eichelmann U[b], Heinesch B[a], Hertel M[c], Janous D[d], Kolle O[c], Lagergren F[e], Lindroth A[e], Minerbi S[f], Moderow U[b], Mölder M[e], Montagnani L[f], Queck R[b], Rebmann C[c], Vestin P[e], Yernaux M[c], Zeri M[c], Ziegler W[c], Aubinet M[a]

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**Abstract** Extensive field measurements have been performed at three CarboEurope-Integrated Project forest sites with different topography (Renon/Ritten, Italian Alps, Italy; Wetzstein, Thuringia, Germany; Norunda, Uppland, Sweden) to evaluate the relevant terms of the carbon balance by measuring $CO_2$ concentrations [$CO_2$] and the wind field in a 3D multitower cube setup. The same experimental setup (geometry and instrumentation) and the same methodology were applied to all the three experiments. It is shown that all sites are affected by advection in different ways and strengths. Everywhere, vertical advection ($F_{VA}$) occurred only at night. During the day, $F_{VA}$ disappeared because of turbulent mixing, leading to a uniform vertical profile of [$CO_2$]. Mean $F_{VA}$ was nearly zero at the hilly site (Wetzstein) and at the flat site (Norunda). However, large, momentary positive or negative contributions occurred at the flat site, whereas vertical non-turbulent fluxes were generally very small at the hilly site. At the slope site (Renon), $F_{VA}$ was always positive at night because of the permanently negative mean vertical wind component resulting from downslope winds. Horizontal advection also occurred mainly at night. It was positive at the slope site and negative at the flat site in the mean diurnal course. The size of

the averaged non-turbulent advective fluxes was of the same order of magnitude as the turbulent flux measured by eddy-covariance technique, but the scatter was very high. This implies that it is not advisable to use directly measured quantities of the non-turbulent advective fluxes for the estimation of net ecosystem exchange (NEE) on e.g. an hourly basis. However, situations with and without advection were closely related to local or synoptic meteorological conditions. Thus, it is possible to separate advection affected NEE estimates from fluxes which are representative of the source term. However, the development of a robust correction scheme for advection requires a more detailed site-specific analysis of single events for the identification of the relevant processes. This paper presents mean characteristics of the advective $CO_2$ fluxes in a first site-to-site comparison and evaluates the main problems for future research.

# ERKLÄRUNG

Hiermit erkläre ich, die vorliegende Arbeit selbstständig und ohne die Hilfe anderer Personen angefertigt zu haben. Weiterhin versichere ich, nur frei zugängliche oder lizenzierte Software verwendet zu haben, welche mir im Rahmen einer Anstellung als wissenschaftlicher Mitarbeiter an der Professur für Meteorologie des Institutes für Hydrologie und Meteorologie der Technischen Universität Dresden zur Verfügung stand.

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Uta Moderow

Dresden, 15.11.2010

# ERRATUM

Following sentence of figure captions 4 and 5 and of table caption 2 should read:

Rainy periods and periods with relative humidity > *97.5 %* were excluded.