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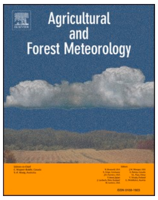

Review

Energy balance closure at FLUXNET sites revisited

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ABSTRACT

The FLUXNET network with numerous eddy covariance stations distributed worldwide is an important backbone for the study of ecosystem-atmosphere interactions. In order to provide reliable data for a variety of related research fields all parts of the ecosystem-atmosphere interactions need to be fully captured. Energy balance closure can be an indicator that all fluxes are fully recorded. However, in an investigation of the FLUXNET data set over 20 years ago, a systematic imbalance of around 20 % was observed in the surface energy balance. By improving measurement instruments and arrangements as well as data post-processing, the imbalance was reduced to about 15 % within the following ten years. We show that the remaining imbalance has hardly changed to this day. In the meantime, it has become clear that the energy transport through mesoscale secondary circulations, which by definition cannot be captured with single-tower eddy covariance measurements, accounts for a large proportion of the remaining imbalance and leads to an underestimation of atmospheric energy fluxes. Storage changes, which have so far only been partially recorded, were also found to strongly contribute to the imbalance. In addition to recommendations for improving storage change measurements, we therefore present various energy balance closure approaches. These can be used to complement FLUXNET measurements by accounting for those flux contributions that cannot be captured by single-tower measurements or to parameterize the transport by secondary circulations in numerical weather and climate models. Another important finding in energy balance closure research is that secondary circulations contribute not only to energy transport but also to the transport of CO_2 and other substances, but more research is needed in this area. We conclude that research into energy balance closure problem has made great progress in recent years, which is crucial for investigating the role of ecosystems in the Earth system.

1. Introduction

The energy-balance closure (EBC) problem is seen as one of most important sources of uncertainty of global data products on ecosystem-scale fluxes of energy, water and CO_2, as they are measured by eddy covariance in the FLUXNET network (Baldocchi et al., 2001). In their analysis of the La Thuile dataset, Stoy et al. (2013) found an average closure per site of 0.85 %, similar to previous and subsequent syntheses (e.g. Wilson et al. 2002, Cui and Chui 2019), which means that the sum of turbulent fluxes of sensible and latent heat are systematically underestimated across FLUXNET sites in different parts of the world. This is of particular concern because FLUXNET is the empirical backbone for our understanding of ecosystem-atmosphere interactions. Global hydrological, ecosystem, and Earth System models that feed assessments like the IPCC reports (e.g. IPCC 2021) are evaluated and calibrated with FLUXNET data. Moreover, flux estimates of trace gases, such as CO_2 and other greenhouse gases, may also be affected by this bias, since both the instrumentation and the underlying turbulent transport mechanisms are the same (Foken et al., 2011).

The lack of energy balance closure is usually expressed in two terms, either as imbalance *Imb*, which is residual of the energy balance equation, where R_{net} is net radiation, G is ground heat flux, and H and LE are the sensible and latent heat fluxes, in units of W m^{-2} (Eq. (1).), or as energy balance ratio *EBR*, which is the ratio between the sum of the turbulent heat fluxes and the available energy at the surface (Eq. (2)) over a given period, which can be between 24 h or several years,

$$Imb = R_{net} - G - H - LE, \tag{1}$$

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$$EBR = \frac{\sum H + LE}{\sum R_{net} - G}. \tag{2}$$

Note that this definition of the energy balance is based on the assumption of an infinitely thin two-dimensional horizontally homogeneous surface and hence no storage terms need to be considered. Alternatively, the imbalance is also defined as *Imb* normalized by the available energy at the surface in the literature when using large-eddy simulations to investigate the EBC problem (e.g. Huang et al. 2008, De Roo et al. 2018, Wanner et al. 2022). Unfortunately, the nomenclature is not fully consistent. Technically speaking, the imbalance has to equal zero if all terms or the energy balance are considered due to the first law of thermodynamics. Nevertheless, the term imbalance is used to denote the unmeasured fluxes. Moreover, the slope of a linear regression model between the sum of the turbulent fluxes and the available energy is used as a measure for EBC. This is certainly a useful measure, but should interpreted with caution since its value depends on the type of regression model that is used for the fitting, e.g. least squares, orthogonal, and with or without intercept, which should equal zero but rarely does in practice.

A first overview on the EBC at FLUXNET sites was given by Wilson et al. (2002). This was also the first time that this problem was shown to be a general phenomenon across flux tower sites, which was crucial for all following research on this subject. The outstanding relevance of this study is also reflected in the extraordinary high citation numbers (1931 citations, retrieved on 09 Sep 2024), which makes it the most cited paper in *Agricultural and Forest Meteorology*. In this study, the mean energy balance gap across sites was quantified for the first time as being in the order of 20 % of the available energy. This study found a clear correlation between the energy balance ratio and friction velocity u* as a measure for the intensity of turbulent mixing, it investigated systematic differences in EBC between open-path and closed-path gas analysers, and it investigated the seasonal variability of EBC. Moreover, Wilson et al., concluded, based on circumstantial evidence, that the EBC problem is linked with the CO_2 fluxes, since the net CO_2 uptake was less for a given value of photosynthetically active radiation when the energy imbalance was greater. It was only possible to describe the EBC problem as a general worldwide phenomenon thanks to this large database of FLUXNET, since data from just one site or region may be influenced by specific instrumental or environmental factors. All these findings of Wilson et al. (2002) described above are still relevant for the ongoing research on EBC today, more than twenty years later.

Stoy et al. (2013) further investigated the EBC at 173 FLUXNET stations over different ecosystems, with a focus on the influence of landscape scale heterogeneity. To investigate the influence of landscape scale heterogeneity on EBC, the FLUXNET dataset was combined with the MODIS plant functional type and enhanced vegetation index product across 20×20 km^2 areas surrounding tower locations to explore the influence of landscape heterogeneity beyond the flux on EBC (Panin et al., 1998; Mauder et al., 2007). Generally, most energy was found to be missing, in absolute terms, under convective daytime conditions, under which the imbalance decreases with increasing friction velocity, confirming the findings of Wilson et al. (2002). The EBR per research site varied strongly across ecosystems, ranging from 0.70 ± 0.19 over deciduous broadleaf forests to 0.94 ± 0.16 over evergreen broadleaf forests. The variations in EBR across vegetation types could be explained primarily by the heterogeneity of landscapes in which the respective vegetation types were typically found, but not the characteristics of the vegetation types themselves. EBR was found to reach around 0.9 over homogeneous landscapes and decreased with increasing landscape heterogeneity. The results of this study suggested further focus on the influence of landscape heterogeneity and mesoscale circulation on surface-atmosphere exchange processes. A Chapman Conference on EBC, which is scheduled for September 2025 in Boulder, CO, exemplifies the continued relevance of the topic.

2. Network-wide energy-balance closure

Network-wide studies on EBC across sites offer a unique potential for the investigation of general issues related to the eddy-covariance theory and its typical application, but few have taken place over the past decade. We analysed energy balance closure from the FLUXNET2015 dataset (Pastorello et al., 2020), which comprises 1532 site-years collected at 212 sites around the world (Fig. 1). The data collected at all 212 sites was processed following the standardized ONEFlux data processing pipeline, which includes state of the art quality control checks, random uncertainty estimation, and gap filling methods. Fig. 1 shows an underestimation of turbulent energy fluxes ($H + LE$) compared to the available energy ($R_{net} - G$) on average across all sites with a regression slope of 82 % from the FLUXNET2015 dataset. This imbalance is not much different from the previous studies of Wilson et al. (2002) or of Stoy et al. (2013) regardless of the efforts in quality assurance and quality control through ONEFlux. While most of the sites show an underestimation of the turbulent fluxes, some sites also show a slight overclosure, which is more likely to occur for sites with lower available energy. This finding can partially be explained by random noise around a mean regression with a slope < 1. Moreover, it is striking that wetlands and evergreen needle-leaf forests (ENF) show a distinct overclosure, with energy balance ratios larger than 1, probably indicating advection of energy from surrounding areas with different land-use/land-cover types. Similar to a previous analysis of Stoy et al. (2013), evergreen broadleaf forests (EBF) and Savannahs show the best closure, with energy balance ratios around 0.9, while croplands and deciduous broadleaf forests (DBF) show the poorest closure of all ecosystem types.

Jung et al. (2019) provide an assessment of global land-atmosphere energy fluxes by upscaling FLUXNET data to the globe by an ensemble of machine learning methods, input data sets, and different ad-hoc energy balance correction scenarios. While the FLUXCOM ensemble estimates for mean global land energy fluxes are within the uncertainty of our state-of-the-art knowledge from independent approaches (Jung et al., 2019), the FLUXCOM ensemble spread is dominated by the range of estimates corresponding to the energy balance correction scenarios (Fig. 2). This implies that the FLUXNET EBC issue is the largest source of uncertainty for quantifying global land energy fluxes by the FLUXCOM approach. Specifically, we find an associated uncertainty range of about 20–30 % for global mean LE and H, which varies for different continents between ~10 and 50 % (Fig. 2).

3. Potential reasons for an energy imbalance at a given site

Careful quality assurance and quality control (Foken et al., 2004; Mauder et al., 2006) and the inclusion of storage fluxes (Leuning et al., 2012) usually leads to an improvement of energy balance closure, in particular for diurnal time scale, and is therefore a prerequisite for further study of the fundamental reasons for the energy imbalance. Moreover, dampening of the water vapour fluctuation by the intake tubes of infra-red gas analysers, particularly, if they are long and the inner walls are not kept clean, can lead to a substantial underestimation of the actual latent heat flux though low-pass filtering (Fratini et al., 2012). It has been discussed that choice of sonic anemometer may also lead to an underestimation of turbulent scalar fluxes due to probe-induced flow distortion effects, particularly for non-orthogonal sonic arrays (Frank et al., 2013), which are very often used in FLUXNET. However, a detailed field intercomparison with a high-resolution 3D Doppler-lidar as reference instrument only found systematic errors of about 1 % of the flux (Mauder et al., 2020, which is almost negligible. Nevertheless, further research is warranted to develop an effective correction for this bias.

Another potential reason for a poor energy balance closure can be the mismatch of footprints between turbulent heat fluxes, net radiation and soil flux, in heterogeneous landscape (Schmid et al., 1997). It is hard to

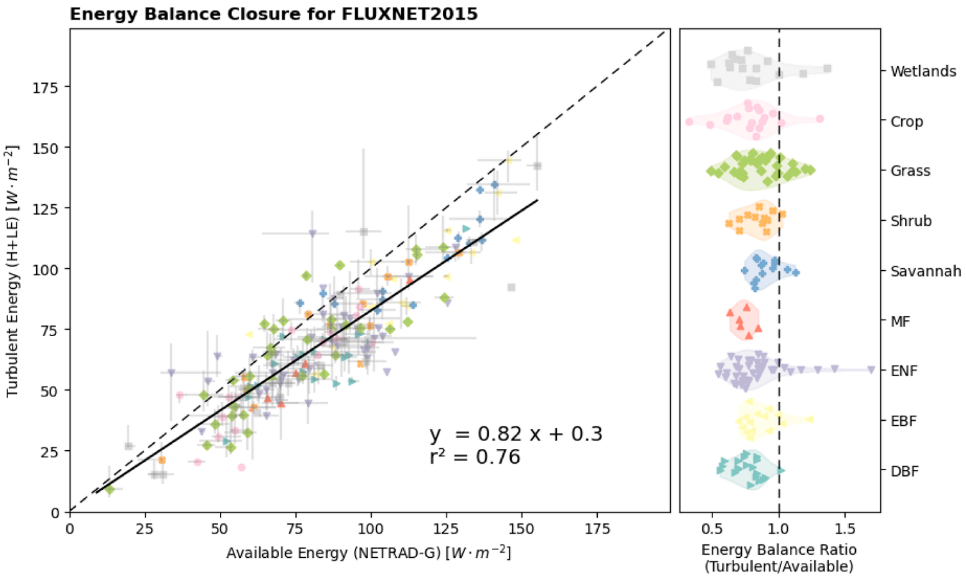

Fig. 1. Energy balance closure of the FLUXNET2015 dataset (Pastorello et al., 2020). Points represent the median across years of mean annual available energy (net radiation minus ground heat flux) to turbulent energy (sensible plus latent heat flux). Error bars represent the variability (5th to 95th percentiles) across years, with all years where at least 60 % of all fluxes were directly measured or gap-filled with high quality estimates (ONEFlux flags 0 or 1). In cases where ground heat flux was not measured, it was assumed to be net zero over the year.

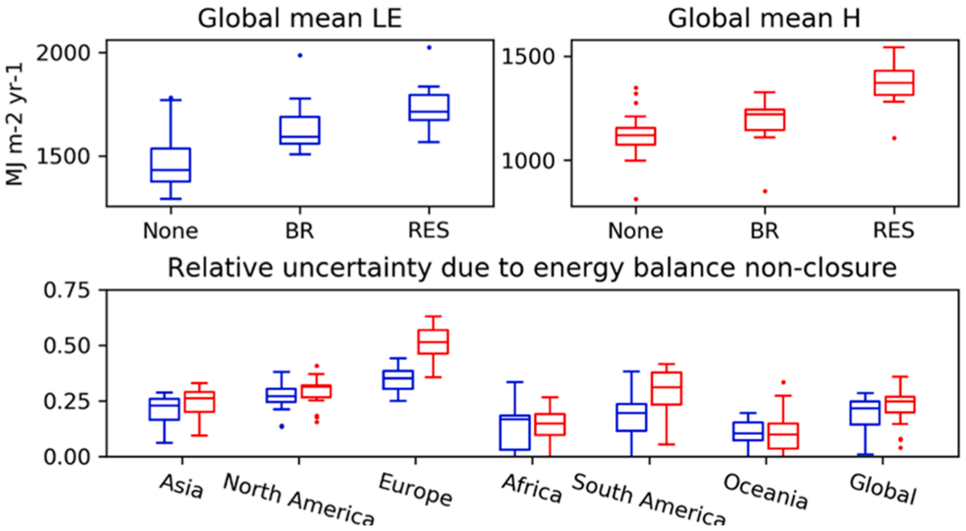

Fig. 2. Importance of the FLUXNET energy balance closure gap for global terrestrial assessments of latent (LE) and sensible (H) heat fluxes based on the full-factorial FLUXCOM ensembles. Top row: Mean LE and H for the global vegetated area for three FLUXNET energy balance closure correction scenarios (None: no correction applied, BR: correction assuming the measured Bowen ratio is correct, RES: assuming all missing energy is in LE or H respectively). Each boxplot shows the distribution of 21 ensemble members of different machine learning models, meteorological forcing, or predictor set. Bottom row: Relative uncertainty of mean LE and H due to energy balance non-closure for different regions calculated as (RES-None)/None. Data are from Jung et al. (2019).

conceive that this mismatch can lead to a systematic error, since neighbouring patches of land cover can sometimes have smaller or larger turbulent heat fluxes. This effect, therefore, normally acts as a random error (Richardson et al., 2012).

For some sites, especially at tall towers over forests, a better energy balance closure can be achieved if the averaging time for the covariance calculation is increased from the conventional 30 min to two or four hours in order to include low-frequency flux contributions (Malhi et al., 2002; 2004; Finnigan et al., 2003; Gerken et al., 2018). In principle, any averaging operator acts as a high-pass filter, thereby leading to a loss of spectral information. If an extension of the averaging time is not practically feasible, this high-pass filtering effect can also be compensated as part of the spectral correction based on model (co-)spectra (Mauder et al., 2021a). A comprehensive overview on potential reasons for an energy imbalance at a given site is provided by Mauder et al. (2020), which can be due to instrumental errors, data processing errors, mismatch of footprints, additional or otherwise neglected sources or sinks of energy, and non-turbulent transport either by *secondary circulations* or by *advection* by the mean flow. Many of these potential reasons can be excluded by conducting measurements carefully or do not create a systematic bias, but neglected storage terms and non-turbulent transport warrant further investigation. Moreover, soil heat flux is often not adequately measured, while both the technique itself and the choice of sampling area and can lead to significant errors using traditional methods (Liebethal et al., 2005; Ochsner et al., 2007; Evett et al., 2012).

Capturing storage accurately posed challenges to the measurement set-up, which, however, can be overcome with some effort, as has been demonstrated for some FLUXNET sites based on vertical profile measurements along one tower (e.g., Haverd et al. 2007, Moderow et al. 2007). In contrast, measuring non-turbulent fluxes requires spatially distributed measurements at several towers (e.g., Oncley et al. 2007, Butterworth et al. 2021), which is not feasible for standard long-term eddy-covariance sites. Hence, these transport terms can only be modelled and then applied as a correction to the measured flux.

Transport through secondary circulations have been identified as one main reason for a systematic underclosure of the energy balance closure. They constitute organized, i.e. non-random or non-chaotic, flow structures that are superimposed on a larger general circulation. For example, roll vortices are one type of secondary circulations. They typically fill the boundary layer across its entire vertical extent, have a width of two to three times the boundary layer depth and a length of several kilometres (e.g. Etling and Brown 1993). It is well established that such rolls are prevalent in daytime convective boundary layers with some amount of background wind. Therefore, they have the potential to explain a general phenomenon, such as the EBC problem. They are quasi-stationary meaning they do not propagate with the mean wind. Therefore, they violate the ergodic hypothesis and also Taylor's frozen turbulence hypothesis (Taylor, 1938), and the associated flux that they transport can never be captured by single-tower measurements, regardless of averaging time (Mahrt, 2010; Cheng et al., 2017). Moreover, the asymmetry of coherent large-scale eddies under convective conditions can lead to a bias in EC flux estimates and hence a lack of EBC (Liu et al., 2021), and the resulting underestimation cannot easily be corrected for. These coherent structures do not follow the classical small-scale isotropic turbulence and hence violate the underlying assumption of eddy-covariance measurements. Instead, secondary circulations produce dispersive fluxes appear as persistent spatial heterogeneities in the temporally averaged flow (Calaf et al., 2022). They can be calculated as the spatial covariance of the temporally averaged fluctuations form the spatio-temporal mean values of vertical velocity and the scalar to be transported, e.g., temperature or specific humidity for the sensible or latent heat flux respectively (Raupach and Shaw, 1982). This is probably one reason why spatially averaging techniques such as scintillometry (Meijninger et al., 2006) and airborne measurements (e.g. Gioli et al. 2004, Mauder et al. 2007) often lead to larger fluxes than tower measurements in the same source area and, hence, better energy balance closure (Foken et al., 2010). For this reason, such measurements have been used to evaluate energy balance closure parameterizations as they can include mesoscale flux contributions (Eder et al., 2014).

4. Overview on energy-balance closure corrections

In many studies, the energy fluxes are reported as measured after all necessary conversions, corrections and quality control (Lee et al., 2004; Mauder et al., 2021b). However, if closed energy budgets are needed for a specific objective, e.g. in hydrology, ecology, or other fields of research, ad-hoc energy balance corrections are often applied. For the lack of a better estimate, these corrections are based on the assumption that the Bowen ratio is preserved, so that the sensible and the latent heat flux are adjusted by the same percentage (e.g. Twine et al. 2000). However, more elaborate correction procedures have been developed recently.

4.1. Thermodynamic approaches

One possibility to describe the problem of EBC and potentially develop a correction model is the use of fundamental laws of thermodynamics. This seems obvious since the energy balance is based on the conservation of energy principle. Traditionally, thermodynamics considers equilibrium states. Real-world processes, such as energy transport in the atmospheric boundary layer, can deviate significantly from this underlying assumption. In the EBC problem, the assumption of thermodynamic equilibrium is challenged by the time-scale of transport processes that are not ensured to be complete in the assumed finite time. This requires the use of non-equilibrium thermodynamics, implying the need to optimize one or more thermodynamically meaningful variables, e.g., the rate of entropy production (Paltridge, 1981; Kleidon et al., 2006). Based on this principle, Li and Wang (2020) have proposed a model that treats the atmospheric boundary layer in the presence of turbulent motion as a heat engine between the hot (surface) and cold (tropopause) reservoirs. They apply this model to data from eight AmeriFlux EC-towers and achieve an average improvement of EBR by 11 %. However, this model relies on input variables that are often not available, only available with a relatively large uncertainty, or that vary across spatial scales smaller than that of the atmospheric boundary layer, i.e., air temperature at the top of the boundary layer for the atmospheric heat engine, and soil diffusivity for the subsurface heat conduction.

4.2. Semi-empirical LES-based approaches

Three-dimensional numerical modelling using large-eddy simulations (LES) is a tool of steadily growing importance for the investigation of turbulent flows and thus also for the investigation of transport processes in the atmospheric boundary layer (Deardorff, 1972; Moeng, 1984; Raasch and Schröter, 2001). It is of particular interest for studies on EBC, since it offers the possibility of carrying out virtual measurements in the LES, whereby potential measurement inaccuracies and uncertain boundary conditions common in field experiments do not disturb investigation of the actual underlying physical process. Furthermore, in contrast to field measurements, the true surface fluxes are known, which facilitates the investigation of the partitioning of the energy balance gap into contributions from H and LE. The first LES study on the EBC problem was conducted by Kanda et al. (2004). Further studies investigated the effect of inhomogeneous heating secondary circulations and explored the possibilities of designing a simplified multi-tower structure in order to capture the otherwise neglected dispersive fluxes (Inagaki et al., 2006; Steinfeld et al., 2007).

The first LES-based correction was developed by Huang et al. (2008), which also included CO_2 in addition to LE and H. However, due to a rather coarse grid spacing of $50\times50\times20$ m, the derived correction could not be applied near the surface at typical tower measurement heights but only higher up in the boundary layer ($>$ 100 m). Subsequently, De Roo et al. (2018) performed a similar experiment at higher resolution, and developed an LES-based correction that can be applied to correct latent and sensible heat fluxes within the surface layer. Both approaches take into account the influence of atmospheric stability, which has been observed as a relevant factor for EBC in a variety of field and LES studies (Barr et al., 2006; Stoy et al., 2006; 2013; Hendricks-Franssen et al., 2010; Zhou et al., 2019), and the measurement height relative to the boundary layer depth.

This correction was developed with the intention that the derived semi-empirical correction function is quasi-universal, analogous to Monin-Obukhov Similarity Theory (Monin and Obukhov, 1954), so that it can be applied to any site at any time in the world without having to perform site-specific LES. This universality assumption has been evaluated for a number of sites with tall and low vegetation by Mauder et al. (2021b) demonstrating that it can help to improve energy balance closure and that the partitioning of the energy balance between H and LE is realistic. However, there may be limitations for more extreme forms of surface heterogeneity, where local advection dominates, since all underlying simulations have been conducted with horizontally homogeneous surface fluxes, thereby not accounting for the effects of landscape-scale heterogeneity.

Building on the work of De Roo et al. (2018), Wanner et al. (2022) developed an advanced correction method that explicitly accounts for thermal surface heterogeneity, which is known to affect energy transport through secondary circulations and thereby influences the magnitude of the energy balance gap (Inagaki et al., 2006; Sühring et al., 2018; Zhou et al., 2019; Margairaz et al., 2020). This approach is applicable for correcting measurements surrounded by heterogeneous landscape pattern of different scales, but it was only developed for the sensible heat flux. An extension of this method to fluxes of latent heat addressing the problem of energy partitioning is currently under development (Wanner et al., 2024, see Section 4.3).

All three approaches are based on the Buckingham-Pi theory (Buckingham, 1914), which is widely used in similarity theory, a common an empirical method to describe turbulent transport with universal relationships between non-dimensionalised variables of fluids (Stull, 1988). Following the Buckingham-Pi theory, non-dimensional groups of variables, which are relevant to the underlying physical processes, are formed. The individual dimensionless variable groups are then used to fit scaling functions, which are added together at the end. Examples of such non-dimensional groups are u_*/w_*, where w_* is the convective velocity scale (Deardorff, 1970), which can be interpreted as a non-local metric for stability of the boundary layer, or z/z_i, which is the ratio between the measurement height and the boundary-layer height.

4.3. Empirically motivated machine-learning approaches

Machine learning (ML) provides novel and powerful ways to predict the evolution of weather and climate processes, and may therefore be useful for the development of an EBC-correction model. ML models are particularly attractive when physical approaches are too complex, computationally too expensive or not feasible due to lacking input data. However, ML models require enough data coverage and the right predictors to achieve accurate and generalized models. Therefore, it is important to feed theoretically meaningful predictors and constraints into ML models for the EBC problem. For example, a principal component analysis can help to identify the dominant driving variables from a wider selection of variables based on the current understanding of the underlying (bio-) physical processes or instrumental problems (Mauder et al., 2018).

Machine learning is particularly adept to tackling EBC issues, which are harder to fundamentally describe. For example, the study of Zhang et al. (2023) utilized a data driven approach to characterise and correct the dampening effects through different types of gas analysers that remains after application of the standard flux corrections. They use relative humidity *RH* as a predictor for the imbalance, since the underestimation of the turbulent fluxes is most apparent during hours when *RH* is higher than 70 %. As this *RH*-dependence is predominantly observed at sites using closed-path EC systems, it cannot be easily characterised analytically from physical processes. Based on this finding, Zhang et al. (2023) applied a ML technique for the non-linear correction of the latent heat flux, assuming that the *RH*-dependent tube dampening effects are the main reason for the observed behaviour. For this high relative humidity correction (HRHC), the algorithm was adapted to enforce the decreasing response of the *LE* measurement to *RH*. It is important to note that this correction does not aim to close the energy balance entirely, but only to correct for the *RH*-dependent underestimation of *LE*, which can be attributed to a low-pass filtering effect of the infra-red gas analyser. Moreover, the magnitude of this correction can and should be minimized by optimizing the measurement set-up, e.g., by heating of the intake tube and keeping it clean and short, and through adequate spectral corrections (e.g., Peltola et al. 2021).

Wanner et al. (2024) combined a machine-learning approach with the semi-empirical and LES-based approach of Wanner et al. (2022) to develop a ML model which directly predicts the dispersive fluxes of sensible and latent heat by secondary circulations separately. Since dispersive fluxes are influenced by a much larger area than the flux tower footprint area, it is more reasonable to model them directly rather than by scaling the turbulent fluxes. The latter would only make sense if the locally measured fluxes were representative of the surrounding landscape, which is typically not the case in heterogeneous landscapes, over which the dispersive fluxes can be particularly high. This study also determined the storage terms in the air layer below the eddy-covariance system in addition to the dispersive fluxes and confirmed that part of the energy balance gap is a result of neglected storage changes, particularly over tall vegetation (Lindroth et al., 2010). The fact that dispersive fluxes are representative of a large area also means that the consideration of dispersive fluxes does not necessarily lead to a perfect closure of the energy balance in single-tower EC measurements at a certain location. However, it can help to remove the systematic bias, and we expect that some form of random scattering around the 1:1 line can be achieved across the network if the modelled dispersive fluxes are added and storage terms are measured.

4.4. Measurement recommendations

As mentioned above, it is of critical importance to measure the storage terms as part of the standard set-up for eddy-covariance sites as described, e.g., by Rebmann et al. (2018), and to apply careful quality control, including a footprint analysis (Mauder et al., 2013). Canopy heat storage, both in the air layer below the EC-system and in the canopy biomass should be measured routinely, as storage terms can constitute a substantial component of the energy balance, especially for tall canopies (e.g. Leuning et al. 2012, Grachev et al. 2020). Moreover, the continuous measurement of the boundary-layer height, e.g., by using ceilometers (e.g. Emeis et al. 2011, Beamesderfer et al. 2023), would be beneficial for the application of semi-empirical approaches for the correction of transport by dispersive fluxes (De Roo et al., 2018; Mauder et al., 2021b; Wanner et al., 2022). Such proximate remote sensing data for the entire boundary layer can also be the basis for further studies on land-atmosphere interactions (Helbig et al., 2021).

In contrast to the secondary circulations, which are larger submesoscale coherent structures, smaller canopy-scale coherent structures of atmospheric transport, so-called ejections (parcels of air leaving the canopy) have larger air temperature variance than sweeps (those entering the canopy) due to heterogeneous surface heating, and these differences in variance increase with increasing atmospheric instability (Liu et al., 2021). This can lead to a flux bias, and hence, it is suggested to add multiple flux systems per tower to account for vertical turbulent flux divergence. The recommendation for multiple, vertically distributed flux systems at one location is also beneficial for quantifying the standard deviation of vertical wind velocity (σ_w) to determine the coupling between above and below-canopy transport in forested ecosystems to ensure that the carbon balance is adequately captured (Jocher et al., 2017; 2018).

Large-scale campaigns including CHEESEHEAD19 (Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors) were motivated in part to understand the impacts of secondary circulations on energy balance closure (Butterworth et al., 2021), which demonstrated the contribution of mesoscale circulations to the surface-atmosphere exchange of *LE* and *H* (Paleri et al., 2022). Few campaigns can allow for such extensive measurements across the atmospheric boundary layer across different vegetative seasons, and it is critical to understand the reasons for a lack of energy balance closure at the flux network scale.

5. Implications and outlook

A systematic underestimation of the turbulent heat fluxes has several implications. The apparent lack of EBC represents a major source of uncertainty of land-surface models due to incomplete calibration data that only include the energy fluxes that can be measured from single-tower EC systems (Kracher et al., 2009). Land-surface models and parameterizations of the atmospheric boundary layer in numerical weather forecasting models are affected by the EBC problem. Land surface models used in numerical weather prediction (NWP) and climate models are validated with the atmospheric energy fluxes measured by single-tower EC stations and therefore neglect the energy transport through secondary circulations (Calaf et al., 2022). With a model of dispersive fluxes, these can be directly predicted in NWP and climate models to account for the total atmospheric energy transport. Hence, the implications of the EBC problem extend beyond single tower or network studies.

Single towers cannot measure dispersive fluxes, which are also one main reason for the lack of EBC in eddy-covariance measurements, thereby hindering progress in this field of science. Moreover, ecological studies, which may, for example, investigate the response of ecosystems to extreme events are affected by a possible underestimation of LE or the CO_2 flux (Reichstein et al., 2007). What is even worse is that the bias might not be constant but seems to/could vary systematically with aridity. This means that any progress in the research on EBC will not only be of interest for micrometeorologists, but also for a number of related disciplines, and these other disciplines may also help to solve this long-standing enigma.

One of the most important questions is the partitioning of the imbalance into contributions of *H* and *LE*. Contradicting findings are reported in the literature, which have been reviewed by Mauder et al. (2020). According to Mauder et al. (2020), there is some evidence that the sensible heat fluxes generally tend to be more underestimated than the latent heat fluxes in relative terms, but there are large site-specific and synoptic differences. This is confirmed by the idealized LES study by Wanner et al. (2024), where the sensible and latent dispersive heat fluxes are approximately equal, while the latent turbulent heat fluxes are significantly greater than the sensible turbulent heat fluxes. The partitioning depends on the differences of potential temperature and specific humidity between the surface layer and the mixed layer, which in turn are controlled by the landscape-scale Bowen ratio and entrainment fluxes. In addition, instrumentation can play a role with profound differences between open-path and closed-path gas analysers (Zhang et al., 2023), which seem to be superimposed on this general behaviour. The mechanisms underlying EBC also vary as a function of environmental conditions that may be compensating; large eddy simulations suggest that *H* is always underestimated by single tower eddy covariance, while *LE* is underestimated when soils are wet and overestimated when soils are dry (Liu et al., 2024). From the global FLUXCOM ensemble data product, we obtain median estimates of global land evapotranspiration that are 68, 75, and 81 thousand cubic kilometres per year corresponding to no correction of *LE*, the Bowen ratio correction, and the residual correction approach respectively (Jung et al., 2019). Our current understanding based on multiple different approaches and perspectives suggests a most plausible range of 65–75 10^3 km^3 yr^{-1} for global land evapotranspiration (Jung et al., 2019), which implies that it seems very unlikely that the FLUXNET EBC gap is dominated by missing *LE*, and rather indicates that *H* might be more strongly underestimated than *LE*.

Finally, one of the biggest unknowns related to EBC are possible implications for the measurement of fluxes of CO_2 and other trace gasses by using the EC method (Foken et al., 2011). The LES-study of Huang et al. (2008) shows that there is an effect for CO_2 of similar magnitude relative to the surface flux, but it behaves differently from the transport of sensible and latent heat due to the differences in typical daytime concentration profiles between these scalars. These differences occur, because *H* and *LE* are typically positive during daytime, while the CO_2 flux is negative over vegetated surfaces. Moreover, the entrainment fluxes at the top of the boundary layer differ from each other, where the fluxes of sensible heat and CO_2 are negative and the latent heat flux through entrainment is positive. Liu et al. (2024) used large eddy simulations to argue that the eddy flux of CO_2 (net ecosystem exchange, NEE) is underestimated when soils are relatively wet and overestimated when soils are relatively dry, which followed the patterns of *LE*. In summary, such effects are likely but mostly unclear in their magnitude. Besides further LES studies including CO_2, data on the increase of biomass over a given period can provide some quantitative comparison (Mauder et al., 2010) acknowledging that changes in soil CO_2 stocks can be difficult to quantify. Over all, decades of research have provided valuable insights into the EBC problem, which is critical to address to better understand the role that ecosystems play in the earth system.

CRediT authorship contribution statement

Matthias Mauder: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Martin Jung:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Paul Stoy:** Writing – review & editing, Writing – original draft. **Jacob Nelson:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Luise Wanner:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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