

Spatial Eddy Covariance from a Multi-Tower Setup for Energy Balance Closure

Hawwa Kadum

hawwa.kadum@kit.edu

Karlsruhe Institute of Technology

Ankur Desai

University of Wisconsin–Madison

Brian Butterworth

National Oceanic and Atmospheric Administration

Sreenath Paleri

University of Wisconsin–Madison

Stefan Metzger

AtmoFacts

Research Article

Keywords: Dispersive Flux, Energy Imbalance, Lacunarity index, Spatial Eddy Covariance, Surface Heterogeneity

Posted Date: July 9th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7044170/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Spatial Eddy Covariance from a Multi - Tower Setup for Energy Balance Closure

Hawwa Kadum · Ankur R. Desai ·
Brian J. Butterworth · Sreenath Paleri ·
Stefan Metzger

Received: DD Month YEAR / Accepted: DD Month YEAR

Abstract We present a novel approach to reducing the surface energy imbalance over heterogeneous terrain by explicitly quantifying dispersive flux contributions using a dense, multi-tower eddy covariance (EC) network. Data were collected during the CHEESEHEAD19 campaign across a 10 km $\times$ 10 km mixed-landscape domain in northern Wisconsin, where 17 EC towers measured momentum, sensible and latent heat fluxes, net radiation, and soil and atmospheric storage from June to October 2019. Two averaging Protocols for computing dispersive fluxes were evaluated: the conventional method (Protocol 1), in which spatial averaging is applied directly to 30-minute tower means, and a proposed ensemble-averaging method (Protocol 2), which temporally aggregates spatial covariances at each time of day across multiple days be-

H. Kadum
Institute for Meteorology and Climate Research-Atmospheric Environmental Research (IMKIFU), Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
E-mail: hawwa.kadum@kit.edu

A. Desai
University of Wisconsin–Madison, Department of Atmospheric and Oceanic Sciences, Madison, WI, USA

B. Butterworth
NOAA/Physical Sciences Laboratory, Boulder, CO, USA
Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder, Boulder CO, USA

S. Paleri
University of Wisconsin–Madison, Department of Atmospheric and Oceanic Sciences, Madison, WI, USA;
Department of Atmospheric Sciences Texas A&M University, College Station, Texas, USA
Ridge, TN, USA

S. Metzger
AtmoFacts, Longmont, CO, USA
CarbonDew, Longmont, CO, USA
University of Wisconsin–Madison, Department of Atmospheric and Oceanic Sciences, Madison, WI, USA

fore spatial averaging. Coordinate rotations using local and global planar-fit methods were also compared. The results show that local planar fit minimizes contamination of vertical velocity signals. Contrary to Protocol 1, the ensemble averaging in Protocol 2 resulted in reducing the energy imbalance. Dispersive sensible and latent heat fluxes accounted for 8% and 38% of their respective total nighttime fluxes, with daytime contributions being smaller but still non-negligible (namely, 1.4% and 16.2%, respectively). Incorporating dispersive fluxes reduced the energy imbalance by 19% on average. A probability density distribution showed that higher energy balance closure percentages occur during nighttime (up to 40% - 90%), while daytime dispersive fluxes closed less than 30% of the imbalance. The results support the proposed hypothesis that heterogeneity-induced spatial structures can be *persistently recurring* rather than *persistently existent*, hence ensemble averaging the covariance of spatial fluctuations over several days can capture these structures more effectively than extending the averaging window or ensemble averaging individual quantities that assume the structure is always existent. While the results demonstrate the ability of the proposed averaging Protocol to capture dispersive fluxes in EC sites, the convective boundary layer results highlight the need for including other heterogeneity-driven terms in the energy balance equation, especially advection.

Keywords Dispersive Flux · Energy Imbalance · Lacunarity index · Spatial Eddy Covariance · Surface Heterogeneity.

1 Introduction

The atmospheric boundary layer (ABL) is the region where turbulent exchanges of energy, momentum, and mass occur actively (Kumar et al., 2006; Brutsaert, 1999). Studying these fluxes is central to atmospheric science because they govern land-atmosphere interactions that underpin weather, climate, agriculture, water management, pollen dispersion, and forest fire behavior (Entekhabi et al., 1996; Pielke et al., 1998; Douglas et al., 2009; Miralles et al., 2019; Schueler and Schlünzen, 2006; Coen et al., 2020; Li et al., 2012). Consequently, turbulent fluxes have been extensively measured and simulated using a wide range of experimental and numerical methods (Kaimal and Finnigan, 1994; Helbig et al., 2021; Butterworth et al., 2021; Metzger et al., 2021; Kanda et al., 2004b; Maronga and Raasch, 2013; Stoll et al., 2020).

Eddy covariance (EC) towers are a common tool for measuring turbulent fluxes (Baldocchi et al., 2001). However, EC systems miss portions of the turbulent spectrum, which contributes to the well known energy imbalance (Culf et al., 2004; Mauder and Foken, 2006; Mauder et al., 2007; Butterworth et al., 2024). Historically, this imbalance was attributed to measurement errors, averaging intervals, and underestimation of soil heat storage (Kukharets and Tsvang, 1999; Kukharets et al., 2000). More recent studies, however, identify surface heterogeneity—variations in topography, temperature, and moisture—as a major contributor. Heterogeneous terrain introduces

low-wavenumber transfer terms, horizontal advection, dispersive fluxes, and secondary circulations that EC towers do not capture (Mauder and Foken, 2006; Mauder et al., 2021; Mahrt, 2014; Kanda et al., 2004a; Zhou et al., 2018; Margairaz et al., 2020; Morrison et al., 2022; Viggiano et al., 2022). Incorporating these non-turbulent contributions has been shown to significantly improve the energy balance closure (Xu et al., 2020; Metzger, 2018; Mauder et al., 2021; Wanner et al., 2022). Figure 1 illustrates literature reported ranges for four major contributors to the energy imbalance.

Storage and low-frequency filtering effects are well documented, typically accounting for 5–10 % of the imbalance (Finnigan et al., 2003; Foken et al., 2006; Lindroth et al., 2010; Xu et al., 2017; Butterworth et al., 2021). In contrast, advection and dispersive flux contributions are less frequently reported. The advection range in Figure 1 draws on Morrison et al. (2022) and Wang et al. (2024). Dispersive flux values are often presented relative to total flux (turbulent + dispersive) rather than the imbalance itself, so the true contribution to the energy imbalance is likely higher than what is shown in the figure (Raupach and Shaw, 1982; Margairaz et al., 2020; Paleri et al., 2025).

The figure illustrates that both advection and dispersive fluxes can substantially influence the energy balance, underscoring the importance of including these terms in EC analyses. Measuring the advection term via EC is challenging: estimating the horizontal component requires resolving horizontal gradients, which in turn demands multiple towers precisely aligned with the prevailing wind direction (Finnigan et al. (2003); Finnigan (2004, 2008); Morrison et al. (2022); Moderow et al. (2021)). Additionally, terrain induced variations and secondary circulations can generate vertical advection that standard EC towers cannot detect. Consequently, this study focuses on quantifying the dispersive flux contribution to the energy imbalance, while the advection term will be addressed in future work using the CHEESEHEAD19 multi-tower experiment.

Interest in dispersive fluxes dates to the 1970s, following temporal and spatial averaging of the mean kinetic-energy equation (Wilson and Shaw, 1977; Raupach and Shaw, 1982). Despite this early recognition, dispersive contributions were often overlooked (Cheng and Castro, 2002; Raupach et al., 1986). Recent work shows they can reach up to 40% of the total flux (dispersive + turbulent) over heterogeneous surfaces under low-wind conditions (Margairaz et al., 2020; Poggi and Katul, 2008; Bailey and Stoll, 2013). Capturing them requires spatial resolutions that resolve relevant turbulent-field variability; large-eddy simulations and laboratory studies are well suited to this task (Poggi et al., 2004; Ali et al., 2019; Calaf et al., 2010; Xie et al., 2008). Understanding dispersive flux contributions is essential for accurately interpreting EC data and addressing energy balance closure issues. Although the FLUXNET network and similar setups provide long-term high quality records, most rely on a few towers. New campaigns like CHEESEHEAD19 and IPAQS use denser EC networks to resolve spatial heterogeneity (Butterworth et al., 2021; Morrison et al., 2021). For CHEESEHEAD19, Xu et al. (2020) showed via large eddy simulations (LES) that one EC tower per 15 km² is needed to

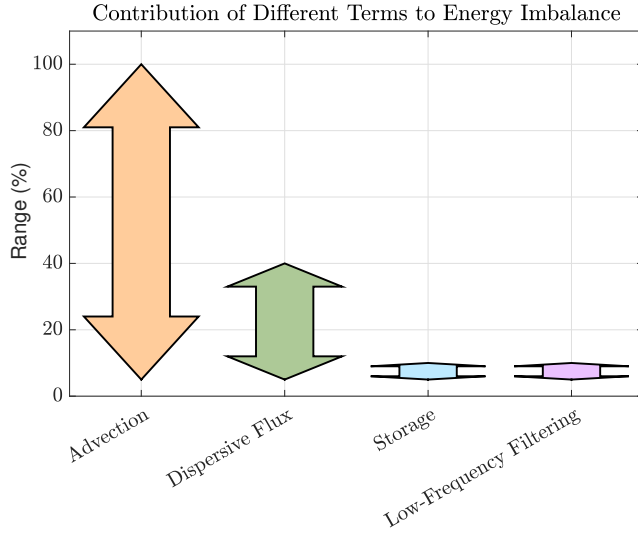


Fig. 1: Literature reported minimum and maximum contributions of four processes to the eddy-covariance energy imbalance: (1) Soil heat storage (Xu et al., 2017; Lindroth et al., 2010; Butterworth et al., 2021); (2) Low frequency filtering (Finnigan et al., 2003; Foken et al., 2006); (3) Advection (Morrison et al., 2022; Wang et al., 2024); (4) Dispersive fluxes (Raupach and Shaw, 1982; Margairaz et al., 2020; Paleri et al., 2025). Storage and low-frequency filtering each typically account for 5–10% of the imbalance. Advection ranges derive from recent field studies. Dispersive flux values are shown relative to total flux (turbulent + dispersive). Hence, the actual contribution to the energy imbalance is higher than indicated.

capture the full domain averaged energy flux. This network’s resolution makes it ideal for examining spatial eddy covariance.

The objectives of this work are presented in Sect. 2. Section 3 describes the measurement site and data processing. Sect. 4 details the spatio-temporal framework and dispersive flux calculations. Results and discussion appear in Sect. 5, followed by conclusions and recommendations in Sect. 6.

2 Objectives

The primary goal of the CHEESEHEAD19 study is to assess how land surface spatial heterogeneity influences the Earth’s surface energy balance using EC data. Previous work demonstrated the contribution of mesoscale eddies to sensible and latent heat fluxes (Paleri et al., 2022) and showed that the CHEESEHEAD19 eddy covariance (EC) tower network in a heterogeneous forest ecosystem is a unique opportunity to investigate drivers of the energy imbalance. In Butterworth et al. (2024), spatio-temporal averaging of EC fluxes

was used to assess dispersive flux effects on the energy imbalance. Although this averaging unexpectedly led to an increased imbalance, two key findings emerged: (1) the imbalance depends primarily on atmospheric stability, and (2) despite a decrease in absolute imbalance from July to October, the ratio of sensible and latent heat fluxes to the available energy remained constant.

These results suggest that consistent drivers (land surface features), such as vegetation and terrain patterns, generate flow structures under similar atmospheric conditions. The results also suggest that since the imbalance is stability dependent, the spatial structures can be *persistently recurrent* rather than *persistently existent*. They reappear in roughly the same spatial location under similar atmospheric conditions due to consistent drivers. We therefore hypothesize that, for comparable stability regimes, these structures recur at the same locations and times of day. Capturing them requires ensemble averaging their covariance at the same time of day over several days to filter out non-recurring structures, turbulent variations, and uncertainty.

Accordingly, this study will:

1. Present an averaging Protocol based on the above hypothesis.
2. Evaluate the spatial domain setup for dispersive flux calculation: whether planar-fit corrections should be applied per site or using the domain-mean streamline.
3. Analyze the diurnal cycle of dispersive fluxes and their potential to reduce the energy imbalance.
4. Investigate how dispersive flux contributions vary with surface heterogeneity, quantified by the lacunarity index (Kadum et al., 2025; Scott et al., 2022; Desai et al., 2022).

3 Data and Site Description

Data for this study were collected during the CHEESEHEAD19 campaign (Butterworth et al., 2021), which took place over a $10 \text{ km} \times 10 \text{ km}$ area of mixed forest, shrubland, grassland, and open water patches in northern Wisconsin, USA. Within this domain (see Figure 2), a network of 17 eddy covariance (EC) towers from NCAR’s LAOF Integrated Surface Flux System (ISFS) (UCAR/NCAR - Earth Observing Laboratory, 1990) worked alongside two additional towers operated by Montana State University and the central AmeriFlux flux tower US-PFa (Desai et al., 2015) to capture the spatial variability of surface-atmosphere exchanges.

Each EC tower measured momentum fluxes together with sensible and latent heat fluxes from June through October 2019. A radiometer provided continuous measurements of net radiation (R_N), while multi-level thermistors and hygrometers recorded profiles of temperature and humidity to estimate atmospheric storage (S_{atmo}). Ground heat flux and soil storage (S_{soil}) were quantified using soil heat flux plates at four depths, along with soil thermistors (Sun et al., 2003).

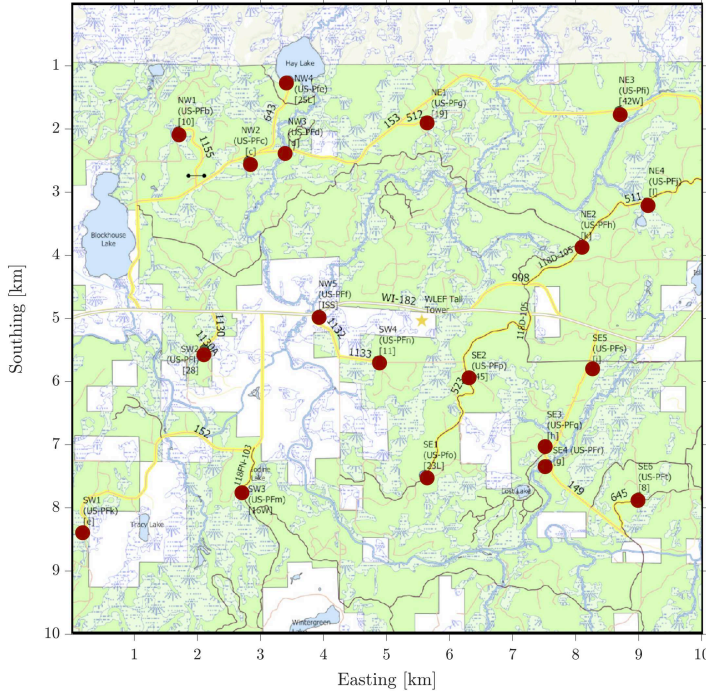


Fig. 2: CHEESEHEAD19 site map showing the locations of eddy covariance towers as red dots. For more details, see Butterworth et al. (2021).

Raw data processing was performed by NCAR and included despiking to remove anomalous records, the Webb–Pearman–Leuning correction (WPL) for density effects (Webb et al., 1980), and high-frequency spectral loss adjustments using the Moore method (Moore, 1986). Data were then block-averaged over 5-minute intervals, subjected to stationarity and quality control tests via the TK3 software suite (Foken and Wichura, 1996; Mauder and Foken, 2015), and aggregated into 30-minute flux periods following the procedure of Foken (1997). Finally, coordinate rotations (either the classic local planar fit or global planar fit approach) were applied to align wind components with the mean flow. Details of these rotation methods and their impact on dispersive flux calculations are discussed in Sect. 5.

4 Theory

4.1 Dispersive Flux for EC measurements

Dispersive fluxes are part of the total fluxes that result from temporally and spatially averaging the momentum and temperature tendency equations Raupach and Shaw (1982). The dispersive flux is added to the turbulent flux to obtain the total flux. Turbulent fluxes are derived from temporal fluctuations

of a given variable (x or y) that is calculated using Reynolds decomposition as follows:

$$x = \bar{x} + x', \quad (1)$$

where, the overbar $[\bar{\cdot}]$ denotes temporal averaging, and the prime $[o']$ denotes fluctuations around this temporal average. In a similar manner, Reynolds decomposition can be performed on spatially averaged quantities;

$$x = \langle x \rangle + x'', \quad (2)$$

where, the angular brackets $[\langle \cdot \rangle]$ denote spatial averaging, and the double prime $[o'']$ denotes the fluctuations around this spatial average. It follows that the spatial averaging of a temporally averaged values obtained from an EC tower network, referred to as spatio-temporal averaging Xu et al. (2020), is described as:

$$\langle \bar{x} \rangle = \bar{x} - \bar{x}''. \quad (3)$$

Conventionally, the dispersive flux is calculated in two ways, directly from spatially averaged covariances Eq. 4 or from multiplying the spatial fluctuations similar to calculating temporal covariances Eq. 5. Figure 3 shows that the fluxes calculated using both equations are identical.

$$\langle \bar{x}'' \bar{y}'' \rangle = \langle \bar{x} \bar{y} \rangle - \langle \bar{x} \rangle \langle \bar{y} \rangle \quad (4)$$

$$\langle \bar{x}'' \bar{y}'' \rangle = \langle \bar{x}'' * \bar{y}'' \rangle \quad (5)$$

In this work, we utilize Eq. 5. The dispersive flux is associated with structures that are persistent over time, necessitating long averaging periods to achieve accurate values (Coceal et al., 2006; Akinlabi et al., 2022; Margairaz et al., 2020). Surface heterogeneity in the CHEESEHEAD19 domain varies hourly throughout the day, as demonstrated by Desai et al. (2022) using the lacunarity heterogeneity scale (Scott et al., 2022). Consequently, averaging over extended time windows within the same day may result in combining periods that do not represent consistent dynamics. To address this issue, we propose a new averaging Protocol for Eq. 5 applied to EC measurements. Instead of directly performing spatial averaging on the spatial fluctuations of 30-minute averages ($\bar{x}_{30m}''$), we first apply temporal averaging (or "ensemble" averaging) for the same time of day across multiple days, provided that no significant weather changes occur during these periods. Also, since these spatial structures are not lasting for a long time, rather recurring consistently under similar atmospheric conditions, the ensemble averaging is performed to the covariance of two quantities ($\bar{x}'' \bar{y}''$) rather than each quantity individually. Following this step, spatial averaging is performed over the EC tower network. This Protocol is based on the hypothesis that similar flow structures are likely to develop

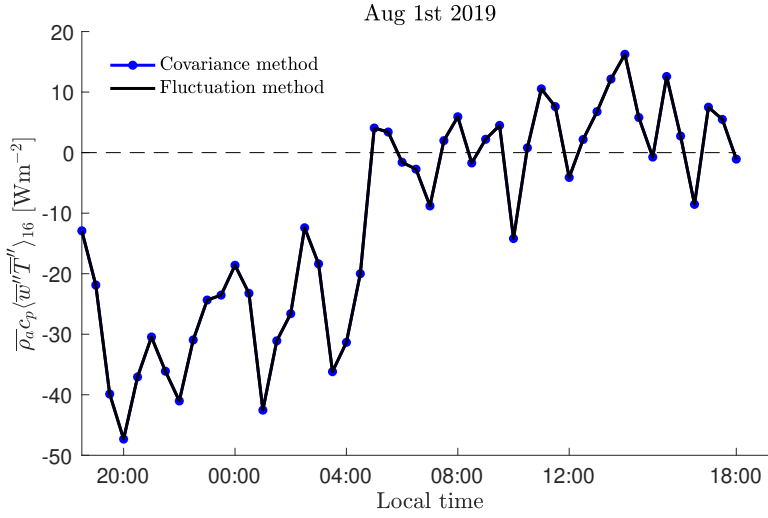


Fig. 3: Diurnal cycle of dispersive sensible heat fluxes. The dispersive parts are calculated using the covariance and the fluctuation methods in Eq. 4 & 5 for August 1st using 16 EC towers.

at similar locations due to consistent causes of heterogeneity, and these structures can be captured by averaging across several days. In contrast, transient structures driven by temporary changes or uncertainty will be filtered out.

In Sect. 5, we will present and discuss the dispersive flux results obtained using both the conventional averaging method (Protocol 1) and the new proposed averaging method (Protocol 2) for Eq. 5. Additionally, we will evaluate different coordinate rotation methods, and examine the contribution of dispersive fluxes to the energy imbalance

5 Results and Discussion

The TK3 software offers two coordinate rotation methods for the EC fluxes, double rotation and planar fit (Wilczak et al., 2001). Since we are interested in the spatial fluctuation of a temporally averaged vertical velocity fluctuations, the double rotation method is not performed because it leads to zero averaged vertical velocity component ($\overline{w} = 0$). However, we investigate whether applying a local planar fit or global planar fit is more suitable for dispersive flux analysis. The local planar fit is the classically applied planar fit coordinate rotation where the rotation matrix and angles are obtained from the local velocity field measured by each EC tower individually. To perform global planar fit, the rotation matrix and angles must be obtained from the global velocity field of the entire domain. This procedure requires a representative velocity field that considers local velocity fields from all towers together.

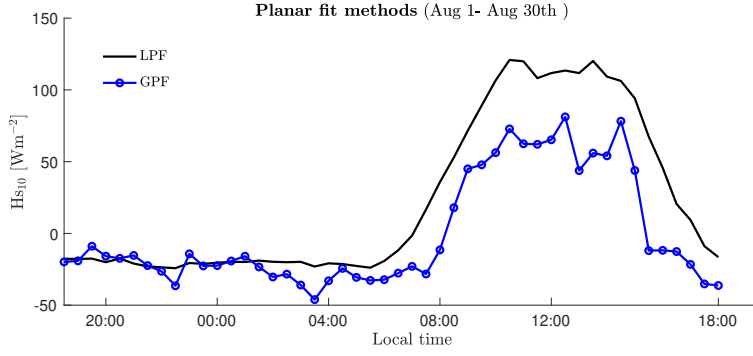


Fig. 4: Diurnal cycle of sensible heat flux. The flux data presented is treated with coordinate rotation using local planar fit (LPF black line) and coordinate rotation using global planar fit (GPF, blue line). The fluxes are temporally averaged over 30 days of August and 10 EC towers.

Figure 4 presents sensible heat fluxes for two different coordinate rotation treatments. The diurnal cycles shown are averaged over 30 days in August, ensuring minimal influence from significant weather or land cover variations due to seasonal changes from the following months. The diurnal cycle for the global planar fit case shows an increase in the nighttime negative sensible heat fluxes and a decrease in afternoon fluxes when compared to the local planar fit. It also shows apparent fluctuations in the fluxes. The global planar fit introduces contamination to the vertical velocity consistent with the findings of a previous study Morrison et al. (2022). For a large and spatially complex domain as the CHEESEHEAD19 field, the global planar fit does not produce reliable results. Local planar fit is the coordinate rotation approach recommended for such heterogeneous domains and is used in the remaining analysis of this work.

The spatio-temporal covariances of two random variables (x and y) given as $\bar{x}''\bar{y}''$ are obtained using two different Protocols. The computation of these fluctuations requires removing the spatio-temporal mean from the 30 minute intervals $[o_{30m}]$. Spatial averaging is always conducted over the number of towers available N . The distinction between the two presented Protocols lies in the step before: Ensemble averaging.

Protocol 1: In this method, a temporal averaging of quantity x over 30 minutes $\bar{x}_{30m}$, then a spatial averaging is performed. The product of this operation $\langle \bar{x}_{30m} \rangle_N$ is used to obtain the spatial fluctuations as follows:

$$\bar{x}_{30m}'' = \bar{x}_{30m} - \langle \bar{x}_{30m} \rangle_N, \quad (6)$$

$$\langle \bar{x}''\bar{y}_{30m}'' \rangle = \langle \bar{x}_{30m}'' * \bar{y}_{30m}'' \rangle_N. \quad (7)$$

Spatial averaging over N EC towers in Eq. 7 yields the dispersive stress, where each tower represents one spatial location. The output of this Protocol is a dispersive flux diurnal cycle per day. These values can then be averaged over several days if a mean value for a certain period of time is needed.

Protocol 2: Temporal averaging performed to study consistently “recurring” mean flow structures requires averaging of these structures over several days to allow for structures that are pertinent to fixed surface features and similar atmospheric conditions to be captured and separated from other temporary structures that don’t recur. The temporal averaging here is performed on the diurnal cycle. Meaning at each time of the day, the values are averaged over d number of days before averaging the fluctuations over N towers. This increases the number of time ensembles for the same time of day.

$$\bar{x}_{30m}'' = \bar{x}_{30m} - \langle \bar{x}_{30} \rangle_N, \quad (8)$$

$$\bar{x}_{30m}'' \bar{y}_{30m}'' = \bar{x}_{30m}'' * \bar{y}_{30m}'', \quad (9)$$

Ensemble averaging over d number of days for each time of the day;

$$\overline{(\bar{x}_{30m}'' \bar{y}_{30m}'')} = \overline{(\bar{x}_{30m}'' * \bar{y}_{30m}'')} , \quad (10)$$

Spatial averaging over N EC towers;

$$\langle \overline{(\bar{x}_{30m}'' \bar{y}_{30m}'')} \rangle_N = \langle \overline{(\bar{x}_{30m}'' * \bar{y}_{30m}'')} \rangle_N. \quad (11)$$

The output of this Protocol is one single dispersive flux diurnal cycle obtained from ensembling (d) number of days.

Figure 5 presents the dispersive sensible and latent heat fluxes (denoted as Hs'' and LE'' from now on as to be differentiated from the turbulent sensible and latent heat fluxes denoted Hs and LE , respectively) calculated using Protocol 1 and Protocol 2. There are minimal differences in the dispersive sensible heat flux between Protocol 1 and Protocol 2. However, the dispersive latent heat flux shows a significant difference between the two methods. Under Protocol 1, the dispersive flux is negative, which contributes to an increase in the energy imbalance. Conversely, Protocol 2 produces a positive dispersive flux.

In Figure 6, the turbulent sensible and latent heat fluxes follow typical diurnal patterns, with peak values observed between 10:00 and 14:00 local time. Latent heat fluxes are higher than sensible heat fluxes, primarily due a substantial amount of energy that is allocated to transpiration, which supports high carbon uptake in temperate mixed forests during the summer season. The dispersive fluxes are averaged across all 16 towers within the domain. Since the domain is heterogeneous in terms of land cover types, the measurement heights of the towers vary depending on the surrounding land cover. Towers located near or on water and grasslands measure at a height of 3 meters, while those in forest canopy sites measure at 30 meters. This vertical elevation difference must be accounted for when performing spatial averaging. To ensure

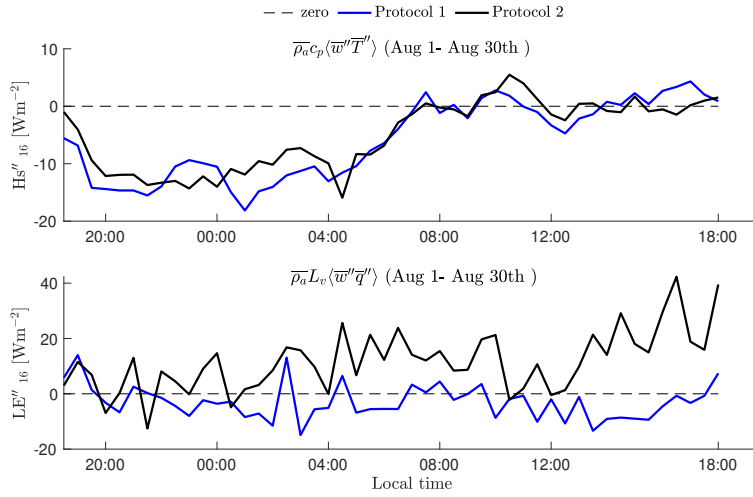


Fig. 5: Diurnal cycle of dispersive fluxes using Protocol 1(blue line) and Protocol 2(black line). Spatial averaging is performed over all 16 towers and temporal averaging over 30 days of August.

consistency, measurements were averaged at the same vertical distance from the ground, as described in Butterworth et al. (2024). Hence, Figure 6 also illustrates the results for dispersive sensible and latent heat fluxes, averaged over 10 eddy covariance (EC) towers. These 10 towers measured fluxes at similar heights (30 m above ground), while the remaining six towers, which measured at different heights, were excluded. Averaging over the same vertical height (10 towers) further increases the captured dispersive fluxes and reduces the negative nighttime dispersive sensible heat flux.

Dispersive fluxes, both sensible and latent, exhibit higher values during the daytime, as shown in the top row of Figure 7. This result coincides with the higher energy imbalance reported during the day, particularly around noon Butterworth et al. (2024). However, the percentage contribution of dispersive fluxes to the total flux follows a different trend, as illustrated in the bottom row of Figure 7. The contribution of dispersive sensible heat flux reaches up to 20% at night but remains below 10% during the day. Similarly, the dispersive latent heat flux contribution peaks at 60% at night and stays under 30% during the day. The dispersive contribution of latent heat flux is notably larger than that of sensible heat flux. The domain is highly heterogeneous in terms of water body distribution, as depicted in Figure 2. Furthermore, the study conducted by Shveytser et al. (2024) showed that evapotranspiration from forested sites contributed the most to latent heat fluxes and environmental variables explained 69% of the variance in half-hourly transpiration.

The difference in the specific heat capacities of water and land results in greater temperature variations, particularly at night when land cools more

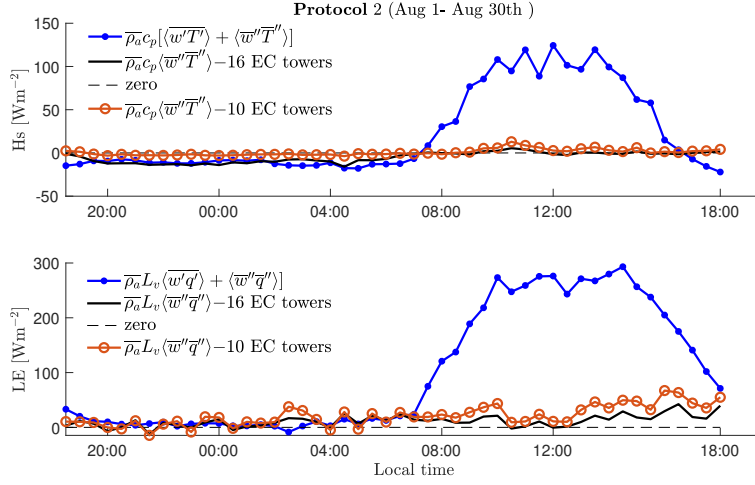


Fig. 6: Diurnal cycle of dispersive and total (turbulent + dispersive) fluxes of sensible (top) and latent (bottom) heat. Spatial averaging is performed over only the 10 EC towers that collect measurements at the same vertical location. The fluxes are temporally averaged over 30 days of August and the dispersive part is calculated using Protocol 2.

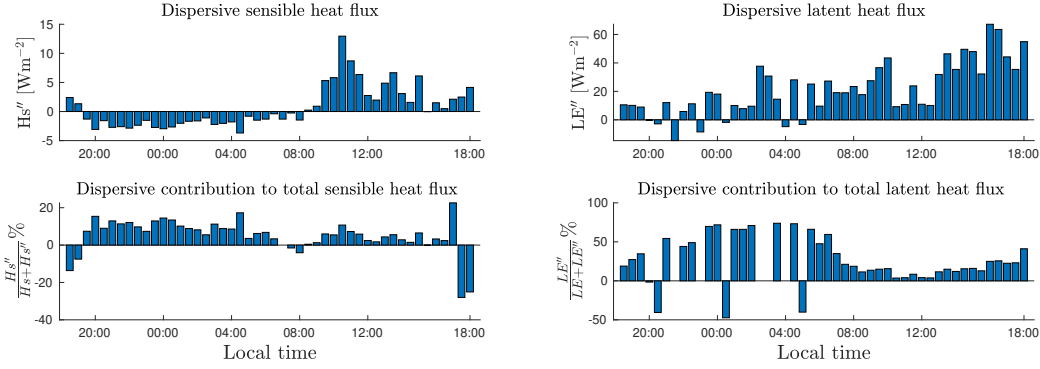


Fig. 7: Bar plots showing, in the top row: Dispersive sensible and latent heat fluxes, and in the bottom row: The contribution of dispersive fluxes to the total flux. The fluxes are averaged over 30 days in August and measured at 30 m above the ground at 10 EC towers.

rapidly than water bodies. The bar plots in Figure 8 illustrate the contributions of turbulent and dispersive components of sensible and latent heat fluxes to the total flux (turbulent + dispersive). These percentages are averaged over daytime (6:00 AM to 6:00 PM) and nighttime (6:00 PM to 6:00 AM). The increased dispersive contributions at night compared to the day-

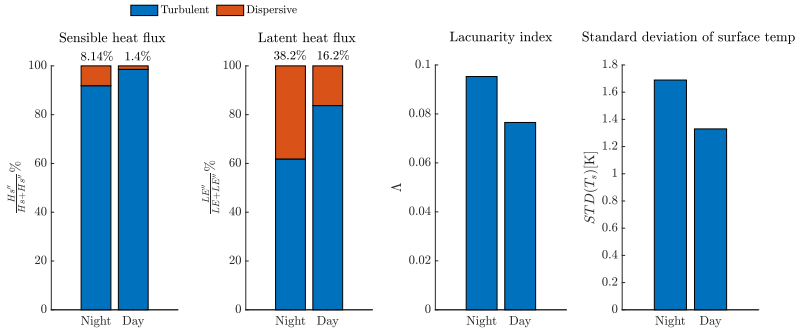


Fig. 8: Bar plots of, from left to right, dispersive sensible heat flux contribution, dispersive latent heat flux contribution, Lacunarity index A , and the standard deviation of land surface temperature. All quantities are averaged for daytime (6:00 AM to 6:00 PM) and nighttime (6:00 PM to 6:00 AM) during August.

time are attributed to the stable boundary layer, which is characterized by reduced turbulent fluxes. Under these conditions, the role of mean flow in energy transport becomes more significant. At night, the stable boundary layer is less effective in blending temperature and humidity differences than the unstable boundary layer during the day. Additionally, the significant nighttime contribution of dispersive latent heat flux indicates airflow moving from drier to moister areas, where evaporation takes place.

Lacunarity analysis is also conducted to quantify the heterogeneity caused by surface temperature distribution. The heterogeneity index (A) is calculated hourly for each day in August using 37-meter resolution land surface temperature (LST) data. The hourly LST map with high spatial resolution was generated using multiple downscaling and data fusion approaches developed by Desai et al. (2021) as part of the CHEESEHEAD19 project. Results were averaged over daytime and nighttime periods, as shown in Figure 8. The plot indicates greater heterogeneity in surface temperature during the nighttime, which coincides with the increased contribution of dispersive fluxes.

The contribution of dispersive fluxes to reducing energy imbalance is examined and presented in Figure 9. Energy imbalance (I_1) is calculated as the difference between net radiation (R_n) and the sum of sensible (H_s), latent (LE), storage (S), and ground (G) heat fluxes. Sensible (H_s'') and latent (LE'') dispersive heat fluxes are then added to compute a new imbalance (I_2), as shown in Figure 9. The results demonstrate that using Protocol 2 to calculate dispersive fluxes captured heterogeneity-induced flow structures not represented in single-site eddy covariance (EC) measurements. Consequently, dispersive fluxes contribute to reducing the energy imbalance.

Combined, sensible and latent dispersive heat fluxes close on average 19% of the energy imbalance. The energy imbalance closure percentage is calculated as $\frac{I_1 - I_2}{I_1} \cdot 100[\%]$ and shown in Figure 10(a). When the imbalance I_1 is close

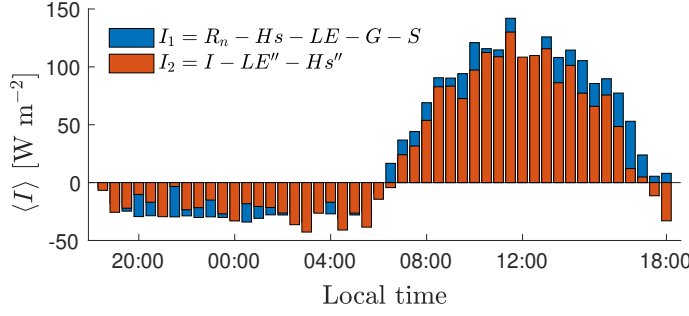


Fig. 9: Energy imbalance averaged over 10 EC towers and 30 days in August. Blue bars are the energy imbalance without dispersive fluxes and orange are the energy imbalance with dispersive fluxes.

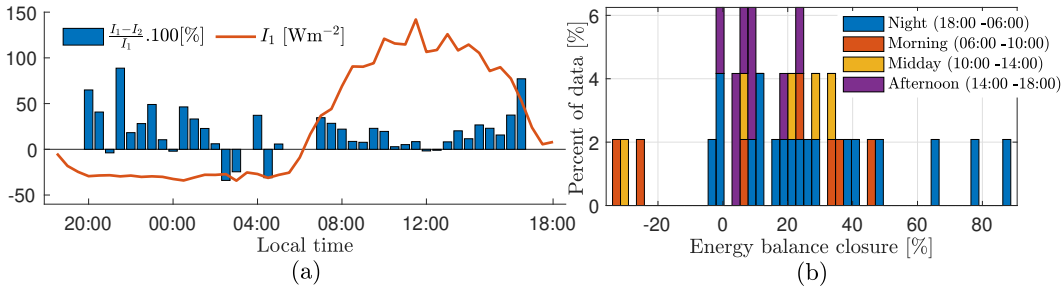


Fig. 10: The contribution of dispersive sensible and latent heat fluxes to closing the energy imbalance (a) and a bar histogram of the energy imbalance closure distribution (b). The data is averaged over 10 EC towers and 30 days in August.

to zero, it results in unreasonably large energy imbalance closure percentages. Hence, such values (9 points in total) have been excluded from the calculations in Figure 10.

During lower I_1 values, associated with nighttime stable boundary layer, the dispersive fluxes covered higher percentages of the imbalance. The probability density distribution in Figure 10(b) shows that higher closure percentages (40%–90%) are associated nearly entirely with nighttime (18:00–06:00). On the other hand, during high I_1 values, midday (10:00–14:00), and afternoon (14:00–18:00), the dispersive fluxes contribute less to closing the energy imbalance. The energy balance closure percentage during these times are below 40% and over 70% of midday hours fall below 30%. This trend is attributed to the fact that using multi-day averaging approach (Protocol 2) captures (semi)stationary, recurring structures. Such structures are the dominant heterogeneity-induced feature during stable boundary layer, while in a convective boundary layer, other heterogeneity-induced terms contribute significantly

to the energy imbalance. For example, vertical advection (not calculated here) is more common in convective conditions (Kaimal et al., 1976; Foken, 2008). In such cases, dispersive flux alone is not enough to close more than 30% of the imbalance.

6 Conclusions

By applying an ensemble-based spatio-temporal averaging approach (Protocol 2) in combination with local planar fit coordinate rotation, we more effectively isolate persistently recurring, heterogeneity-driven motions than with standard averaging method (Protocol 1). These dispersive sensible and latent heat fluxes, typically challenging to obtain from EC measurements, account for a sizable fraction of the total exchange –up to 8.14% and 38.2% at night, respectively– and on average close 19% of the eddy covariance energy imbalance. Crucially, nocturnal conditions yield markedly higher closure than daytime, reflecting the dominance of stationary flow structures under stable stratification.

Our results underscore two key recommendations. First, multi-day, time-of-day ensemble averaging can become a standard step in EC data processing to capture recurring dispersive fluxes over heterogeneous terrain. Such results are valuable to the development of a model to predict EC energy imbalance and correct for it without the need for extensive multi-site setups. Corrected EC measurements have positive implications for weather stations used as input for weather prediction models and for long term flux monitoring sites. Second, incorporating complementary estimates of advective transport (both vertical and horizontal) is essential to further reduce the remaining gap and deliver more balanced energy budgets.

Acknowledgment

H. Kadum acknowledges the Helmholtz Association funding (YIG-Prep-Pro). Authors acknowledge the US National Science Foundation (NSF) funds Nr.1822420 and Nr.2313772 as well as DOE Ameriflux Management Project.

References

- Akinlabi E, Maronga B, Giometto MG, Li D (2022) Dispersive fluxes within and over a real urban canopy: a large-eddy simulation study. *Boundary-Layer Meteorology* 185(1):93–128
- Ali N, Bossuyt J, Viggiano B, Ganapathisubramani B, Meyers J, Cal R (2019) Boundary layer development over a staggered multifractal roughness array. In: 11th International Symposium on Turbulence and Shear Flow Phenomena, vol 30

- Bailey BN, Stoll R (2013) Turbulence in sparse, organized vegetative canopies: a large-eddy simulation study. *Boundary-layer meteorology* 147(3):369–400
- Baldocchi D, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Evans R, et al. (2001) Fluxnet: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* 82(11):2415–2434
- Brutsaert W (1999) Aspects of bulk atmospheric boundary layer similarity under free-convective conditions. *Reviews of geophysics* 37(4):439–451
- Butterworth BJ, Desai AR, Townsend PA, Petty GW, Andresen CG, Bertram TH, Kruger EL, Mineau JK, Olson ER, Paleri S, et al. (2021) Connecting land–atmosphere interactions to surface heterogeneity in cheesehead19. *Bulletin of the American Meteorological Society* 102(2):E421–E445
- Butterworth BJ, Desai AR, Durden D, Kadum H, LaLuzerne D, Mauder M, Metzger S, Paleri S, Wanner L (2024) Characterizing energy balance closure over a heterogeneous ecosystem using multi-tower eddy covariance. *Frontiers in Earth Science* 11:1251,138
- Calaf M, Meneveau C, Meyers J (2010) Large eddy simulation study of fully developed wind-turbine array boundary layers. *Physics of fluids* 22(1):015,110
- Cheng H, Castro IP (2002) Near wall flow over urban-like roughness. *Boundary-Layer Meteorology* 104(2):229–259
- Coceal O, Thomas T, Castro I, Belcher S (2006) Mean flow and turbulence statistics over groups of urban-like cubical obstacles. *Boundary-Layer Meteorology* 121:491–519
- Coen JL, Schroeder W, Conway S, Tarnay L (2020) Computational modeling of extreme wildland fire events: a synthesis of scientific understanding with applications to forecasting, land management, and firefighter safety. *Journal of Computational Science* 45:101,152
- Culf AD, Foken T, Gash JH (2004) The energy balance closure problem. In: *Vegetation, water, humans and the climate*, Springer, pp 159–166
- Desai AR, Xu K, Tian H, Weishampel P, Thom J, Baumann D, Andrews AE, Cook BD, King JY, Kolka R (2015) Landscape-level terrestrial methane flux observed from a very tall tower. *Agricultural and Forest Meteorology* 201:61–75
- Desai AR, Khan AM, Zheng T, Paleri S, Butterworth B, Lee TR, Fisher JB, Hulley G, Kleynhans T, Gerace A, et al. (2021) Multi-sensor approach for high space and time resolution land surface temperature. *Earth and Space Science* 8(10):e2021EA001,842
- Desai AR, Paleri S, Mineau J, Kadum H, Wanner L, Mauder M, Butterworth BJ, Durden DJ, Metzger S (2022) Scaling land-atmosphere interactions: Special or fundamental?
- Douglas E, Beltrán-Przekurat A, Niyogi D, Pielke Sr R, Vörösmarty C (2009) The impact of agricultural intensification and irrigation on land–atmosphere interactions and indian monsoon precipitation—a mesoscale modeling perspective. *Global and Planetary Change* 67(1-2):117–128

- Entekhabi D, Rodriguez-Iturbe I, Castelli F (1996) Mutual interaction of soil moisture state and atmospheric processes. *Journal of Hydrology* 184(1-2):3–17
- Finnigan J (2004) A re-evaluation of long-term flux measurement techniques part ii: coordinate systems. *Boundary-Layer Meteorology* 113:1–41
- Finnigan J (2008) An introduction to flux measurements in difficult conditions. *Ecological Applications* 18(6):1340–1350
- Finnigan JJ, Clement R, Malhi Y, Leuning R, Cleugh H (2003) A re-evaluation of long-term flux measurement techniques part i: averaging and coordinate rotation. *Boundary-Layer Meteorology* 107:1–48
- Foken T (1997) Results of the LINEX-96/2 Experiment. DWD, Geschäftsbereich Forschung und Entwicklung
- Foken T (2008) The energy balance closure problem: An overview. *Ecological Applications* 18(6):1351–1367
- Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. *Agricultural and forest meteorology* 78(1-2):83–105
- Foken T, Wimmer F, Mauder M, Thomas C, Liebethal C (2006) Some aspects of the energy balance closure problem. *Atmospheric Chemistry and Physics* 6(12):4395–4402
- Helbig M, Gerken T, Beamesderfer ER, Baldocchi DD, Banerjee T, Biraud SC, Brown WO, Brunsell NA, Burakowski EA, Burns SP, et al. (2021) Integrating continuous atmospheric boundary layer and tower-based flux measurements to advance understanding of land-atmosphere interactions. *Agricultural and Forest Meteorology* 307:108,509
- Kadum H, Scott R, Smith SE, Calaf M, Cal RB (2025) Momentum transport in heterogeneous forest canopies. *Boundary-layer meteorology* 191(1)
- Kaimal J, Wyngaard J, Haugen D, Coté O, Izumi Y, Caughey S, Readings C (1976) Turbulence structure in the convective boundary layer. *Journal of Atmospheric Sciences* 33(11):2152–2169
- Kaimal JC, Finnigan JJ (1994) *Atmospheric boundary layer flows: their structure and measurement*. Oxford university press
- Kanda M, Inagaki A, Letzel MO, Raasch S, Watanabe T (2004a) Les study of the energy imbalance problem with eddy covariance fluxes. *Boundary-Layer Meteorology* 110(3):381–404
- Kanda M, Moriwaki R, Kasamatsu F (2004b) Large-eddy simulation of turbulent organized structures within and above explicitly resolved cube arrays. *Boundary-Layer Meteorology* 112(2):343–368
- Kukharets V, Tsvang L (1999) Variations in the underlying surface temperature and the problem of closure of the heat balance equation. *Izvestiya Atmospheric and Oceanic Physics* 35(2):188–194
- Kukharets V, Nalbandyan H, Foken T (2000) Thermal interactions between the underlying surface and a nonstationary radiation flux. *Izvestiya, Atmospheric and Oceanic Physics* 36(3):318–325
- Kumar V, Kleissl J, Meneveau C, Parlange MB (2006) Large-eddy simulation of a diurnal cycle of the atmospheric boundary layer: Atmospheric stability and scaling issues. *Water resources research* 42(6)

- Li F, Zeng X, Levis S (2012) A process-based fire parameterization of intermediate complexity in a dynamic global vegetation model. *Biogeosciences* 9(7):2761–2780
- Lindroth A, Mölder M, Lagergren F (2010) Heat storage in forest biomass improves energy balance closure. *Biogeosciences* 7(1):301–313
- Mahrt L (2014) Stably stratified atmospheric boundary layers. *Annu Rev Fluid Mech* 46(1):23–45
- Margairaz F, Pardyjak ER, Calaf M (2020) Surface thermal heterogeneities and the atmospheric boundary layer: the relevance of dispersive fluxes. *Boundary-Layer Meteorology* 175(3):369–395
- Maronga B, Raasch S (2013) Large-eddy simulations of surface heterogeneity effects on the convective boundary layer during the litfass-2003 experiment. *Boundary-Layer Meteorology* 146(1):17–44
- Mauder M, Foken T (2006) Impact of post-field data processing on eddy covariance flux estimates and energy balance closure. *Meteorologische Zeitschrift* 15(6):597–610
- Mauder M, Foken T (2015) Documentation and instruction manual of the eddy-covariance software package tk3 (update). Eigenverlag
- Mauder M, Desjardins RL, MacPherson I (2007) Scale analysis of airborne flux measurements over heterogeneous terrain in a boreal ecosystem. *Journal of Geophysical Research: Atmospheres* 112(D13)
- Mauder M, Ibrom A, Wanner L, De Roo F, Brügger P, Kiese R, Pilegaard K (2021) Options to correct local turbulent flux measurements for large-scale fluxes using a les-based approach. *Geosci Model Dev Discuss* [preprint]
- Metzger S (2018) Surface-atmosphere exchange in a box: Making the control volume a suitable representation for in-situ observations. *Agricultural and Forest Meteorology* 255:68–80
- Metzger S, Durden D, Paleri S, Sühling M, Butterworth BJ, Florian C, Mauder M, Plummer DM, Wanner L, Xu K, et al. (2021) Observing system simulation experiments double scientific return of surface-atmosphere synthesis. *Earth and Space Science Open Archive* 55
- Miralles DG, Gentile P, Seneviratne SI, Teuling AJ (2019) Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences* 1436(1):19–35
- Moderow U, Grünwald T, Queck R, Spank U, Bernhofer C (2021) Energy balance closure and advective fluxes at advex sites. *Theoretical and Applied Climatology* 143:761–779
- Moore C (1986) Frequency response corrections for eddy correlation systems. *Boundary-Layer Meteorology* 37(1):17–35
- Morrison T, Calaf M, Higgins CW, Drake SA, Perelet A, Pardyjak E (2021) The impact of surface temperature heterogeneity on near-surface heat transport. *Boundary-Layer Meteorology* 180(2):247–272
- Morrison T, Pardyjak ER, Mauder M, Calaf M (2022) The heat-flux imbalance: The role of advection and dispersive fluxes on heat transport over thermally heterogeneous terrain. *Boundary-Layer Meteorology* 183(2):227–247

- Paleri S, Desai AR, Metzger S, Durden D, Butterworth BJ, Mauder M, Kohnert K, Serafimovich A (2022) Space-scale resolved surface fluxes across a heterogeneous, mid-latitude forested landscape. *Journal of Geophysical Research: Atmospheres* 127(23):e2022JD037,138
- Paleri S, Wanner L, Sühling M, Desai AR, Mauder M, Metzger S (2025) Impact of surface heterogeneity induced secondary circulations on the atmospheric boundary layer. *Boundary-Layer Meteorology* 191(1):3
- Pielke RA, Avissar R, Raupach M, Dolman AJ, Zeng X, Denning AS (1998) Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global change biology* 4(5):461–475
- Poggi D, Katul GG (2008) The effect of canopy roughness density on the constitutive components of the dispersive stresses. *Experiments in Fluids* 45(1):111–121
- Poggi D, Katul G, Albertson J (2004) A note on the contribution of dispersive fluxes to momentum transfer within canopies. *Boundary-layer meteorology* 111(3):615–621
- Raupach M, Coppin P, Legg B (1986) Experiments on scalar dispersion within a model plant canopy part i: The turbulence structure. *Boundary-Layer Meteorology* 35(1):21–52
- Raupach MR, Shaw R (1982) Averaging procedures for flow within vegetation canopies. *Boundary-layer meteorology* 22(1):79–90
- Schueler S, Schlünzen KH (2006) Modeling of oak pollen dispersal on the landscape level with a mesoscale atmospheric model. *Environmental Modeling & Assessment* 11(3):179–194
- Scott R, Kadum H, Salmaso G, Calaf M, Cal RB (2022) A lacunarity-based index for spatial heterogeneity. *Earth and Space Science* 9(8):e2021EA002,180
- Shveytser V, Stoy PC, Butterworth B, Wiesner S, Skaggs TH, Murphy B, Wutzler T, El-Madany TS, Desai AR (2024) Evaporation and transpiration from multiple proximal forests and wetlands. *Water Resources Research* 60(1):e2022WR033,757
- Stoll R, Gibbs JA, Salesky ST, Anderson W, Calaf M (2020) Large-eddy simulation of the atmospheric boundary layer. *Boundary-Layer Meteorology* 177(2):541–581
- Sun J, Burns S, Delany A, Oncley S, Horst T, Lenschow D (2003) Heat balance in the nocturnal boundary layer during cases-99. *Journal of Applied Meteorology* 42(11):1649–1666, DOI 10.1175/1520-0450(2003)042<1649:HBITNB>2.0.CO;2
- UCAR/NCAR - Earth Observing Laboratory (1990) NCAR Integrated Surface Flux System (ISFS)
- Viggiano B, Bossuyt J, Ali N, Meyers J, Cal RB (2022) Secondary motions above a staggered multi-scale rough wall. *Journal of Fluid Mechanics* 941
- Wang T, Alfieri J, Mallick K, Arias-Ortiz A, Anderson M, Fisher JB, Girotto M, Szutu D, Verfaillie J, Baldocchi D (2024) How advection affects the surface energy balance and its closure at an irrigated alfalfa field. *Agricultural and Forest Meteorology* 357:110,196

- Wanner L, Calaf M, Mauder M (2022) Incorporating the effect of heterogeneous surface heating into a semi-empirical model of the surface energy balance closure. *PloS one* 17(6):e0268,097
- Webb EK, Pearman GI, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society* 106(447):85–100
- Wilczak JM, Oncley SP, Stage SA (2001) Sonic anemometer tilt correction algorithms. *Boundary-layer meteorology* 99(1):127–150
- Wilson NR, Shaw RH (1977) A higher order closure model for canopy flow. *Journal of Applied Meteorology* (1962-1982) pp 1197–1205
- Xie ZT, Coceal O, Castro IP (2008) Large-eddy simulation of flows over random urban-like obstacles. *Boundary-layer meteorology* 129(1):1–23
- Xu K, Sühling M, Metzger S, Durden D, Desai AR (2020) Can data mining help eddy covariance see the landscape? a large-eddy simulation study. *Boundary-Layer Meteorology* 176(1):85–103
- Xu Z, Ma Y, Liu S, Shi W, Wang J (2017) Assessment of the energy balance closure under advective conditions and its impact using remote sensing data. *Journal of Applied Meteorology and Climatology* 56(1):127–140
- Zhou Y, Li D, Liu H, Li X (2018) Diurnal variations of the flux imbalance over homogeneous and heterogeneous landscapes. *Boundary-Layer Meteorology* 168(3):417–442