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Re-evaluating long-time lysimeter data series using a modern mini lysimeter

Conall Ruth[1], Dominik Michel[1*], Martin Hirschi[1] und Sonia I. Seneviratne[1]

Summary

The 40-year lysimeter-based evapotranspiration (ET) time series from the ETH research catchment in Rietholzbach, Switzerland has recently been compared to eddy-covariance flux measurements (Hirschi et al. 2016). While the two methods agree well in terms of monthly and annual time scales, larger discrepancies are found on the daily and sub-daily time scale due to fundamental methodological differences of the compared instruments. Uncertainty of the lysimeter is to a large extent produced by including precipitation from a tipping bucket, which is typically affected by undercatch. This may lead to unrealistic amounts and frequency of condensation. In addition, seepage is measured as the un- controlled gravitational outflow from the lower boundary. In order to determine ET and condensation more accurately, i.e., without the effect of precipitation undercatch and overestimation of seepage due to preferential flow, the long time series is evaluated with a Smartfield mini lysimeter, which can adjust the lower boundary according to a reference observation of soil moisture, and operates with a high temporal resolution of one minute. Increased drying rates at the lysimeter surface as possible effects of preferential flow within the soil column are being observed with a thermal infrared camera, which is used to identify inhomogeneities of the soil surface temperature between the lysimeter and the reference area. The results are used to characterize the accuracy and spatial representativeness of the long lysimeter-based evapotranspiration time series.

Keywords: lysimeter comparison, lower boundary, precipitation, under-catch

Introduction

For many aspects of hydro-meteorological, climatological, ecological and agronomical research it can be important to have accurate estimates of the full set of water balance components. This comprises actual evapotranspiration (ET; which we define as an upward flux only) precipitation (which can be either true, meteorological precipitation or condensation), and seepage (which we define as a net downward flux). Weighing lysimeters are a well-established means of estimating ET and seepage, and are commonly used for validating hydrological models (e.g. Chapman and Malone 2002, Soldevilla-Martinez et al. 2014) and investigating the water use strategies of particular plant types (e.g. Ko et al. 2009, Piccinni et al. 2009, Girona et al. 2011). They can also be used to evaluate other hydrometeorological instruments and measurement techniques, such as eddy-covariance measurements of ET (e.g. Ding et al. 2010, Hirschi et al. 2016). At the Rietholzbach research catchment in northeastern Switzerland, ET is estimated in a number of ways, including the use of a large free-drainage weighing lysimeter in operation since 1976 and a recently-installed, state-of-the-art, weighing mini-lysimeter with a pump-controlled lower boundary. Advances in lysimeter weighing technology, installation procedure and lower boundary design, have greatly improved the precision of the resulting ET and seepage estimates, with modern devices typically possessing weighing resolutions equivalent to 0.01 mm (Fank and Klammler 2013). This has additionally made it possible to reliably measure precipitation (e.g. Schrader et al. 2013, Hoffmann et al. 2016) and condensation (e.g. Meissner et al. 2007, Nolz et al. 2014) using lysimeters. Because of these advances, it is desirable to compare the measurements from the Rietholzbach's mini-lysimeter to those of the large lysimeter to a) assess the quality of the historical large lysimeter ET and seepage records and b) determine if and how the current large lysimeter processing approach can be improved in a retrospectively-applicable manner. Additionally, the high-precision precipitation estimate from the mini-lysimeter can be compared to the reference tipping bucket (Joss-Tognini type Lambrecht 1518 H3, Göttingen) record of precipitation from the same site, to assess its quality as a reference.

Due to the high temporal and absolute resolution of the mini-lysimeter mass measurements, a relatively high degree of noise may be present, which mainly results from mechanical vibration of the lysimeter due to wind (Xiao et al. 2009). Therefore, prior to these analyses, it is of great importance to filter the mass measurements to minimize this noise and allow an accurate estimation the vertical water fluxes. To this end, a number of possible filters have been suggested, including basic moving averages, Savitzky-Golay filters (Savitzky and Golay 1964; as implemented by Vaughan and Ayers 2009, Schrader et al. 2013), spline and sigmoid smoothing (Nolz et al. 2013), and adaptive techniques, such as the Adaptive Window and Adaptive Threshold (AWAT) filter, introduced by Peters et al. (2014). In addition to examining the large lysimeter performance, the comparison of the measured fluxes from each of the lysimeters and the tipping bucket first allows us to broadly assess a number of these mini-lysimeter filters, such that the optimal one can be identified and applied.

[1] Institute for Atmospheric and Climate Science, ETH Zürich, Universitätsstraße 16, CH-8092 ZÜRICH
[*] Ansprechpartner: Dr. Dominik Michel, dominik.michel@env.ethz.ch

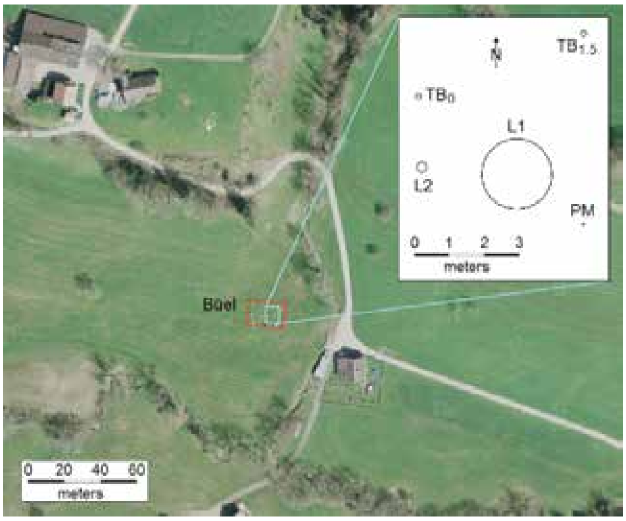

Figure 1: **Aerial photograph of the Buel measurement site (perimeter shown in red) and surrounding area (Federal Office of Topography, COGIS (Coordination, Geo-Information and Services)). Inset is a plan schematic of part of the measurement site, showing the horizontal sampling areas and relative positions of the large lysimeter (L1), mini-lysimeter (L2), 1.5-m tipping bucket ($TB_{1.5}$), ground-level tipping bucket (TB_0) and the precipitation monitor (PM).**

Measurement site

The Rietholzbach catchment is a small pre-alpine watershed located within the Thur river basin in northeastern Switzerland. The catchment has an area of 3.31 km² and covers an altitude range of 682 to 950 m asl. The area is sparsely populated, mainly consisting of pastureland (71.9%) and forest (25.6%). The main soil types present in the catchment are cambisol (40.7%), gleysol (23.9%), gleyic cambisol (17.7%) and regosol (17.6%) (Seneviratne et al. 2012). The region is characterized by a temperate humid climate with a mean air temperature of 7.1 °C and a mean annual precipitation of 1438 mm (Hirschi et al. 2016). Since 1975, the Rietholzbach catchment has been used by ETH Zürich for conducting a variety of hydro-meteorological research. The main measurement station, from which all of the data for this study were gathered, is located at Büel (47.38 °N, 8.99 °E, see https://s.geo.admin.ch/6de2dcf3b5). *Figure 1* shows an aerial view of the measurement station and the surrounding area, with an inset schematic highlighting the instrumentation relevant to this study. The study period spanned 13 months, from 1 Sept. 2015 to 30 Sept. 2016. For most of the analyses, however, the data from 1 Nov. 2015 to 30 Apr. 2016 were omitted due to the presence of snow in these months, as this could distort the lysimeter mass measurements through snow drift and snow bridges (Hirschi et al. 2016). Moreover, the presence of both liquid and solid precipitation would lead to a high temporal variability in the degree of wind-induced precipitation under-catch with the tipping bucket (WMO 2008), which we thus avoid.

Instrumentation

Large lysimeter

The large weighing lysimeter in Büel has been providing continuous ET and seepage measurements since 1976. It has a surface area of 3.14 m² (2-m diameter) and a depth of 2.5 m. The surface is grass-covered and reflects the conditions of the surroundings, in terms of soil structure, composition, cutting and fertilization. The container is synthetic and backfilled with gleyic cambisol, except for a filter layer (gravel and sand) between 2 and 2.5-m depth to prevent damming (Seneviratne et al. 2012). The lysimeter's three load cells have a combined resolution of 100 g, which corresponds to a water column of approximately 0.032 mm. The drainage, which occurs by gravitation only, is measured with a 50-ml tipping bucket, yielding a resolution of approximately 0.016 mm. The drawbacks of this free-drainage design are that the soil at the lysimeter base must be saturated for seepage to occur (Weller et al. 2014), and that capillary rise cannot be represented. Since 1999, the lysimeter mass and seepage have been recorded every five minutes, and can then be compiled into hourly values. For a schematic of the large lysimeter, please refer to Seneviratne et al. (2012).

Mini-lysimeter

The mini-lysimeter (SFL-600, Meter Group, Munich) was installed in Büel in August 2015. It has a surface area of approximately 0.071 m² (0.3-m diameter) and a depth of 0.6 m. The soil column is monolithic and thus represents an undisturbed soil profile. As with the large lysimeter, the surface is grass-covered and reflects the conditions of the surroundings. At the lysimeter base, the soil matrix potential is continuously measured and compared to a reference measurement at the same depth in the undisturbed surroundings. A bi-directional pump connecting a series of suction cups at the lysimeter base to an external drain water bottle is then used to adjust the lysimeter water content to equilibrate these records. This design thus allows for seepage at non-saturated conditions and for (equivalent) capillary rise, which cannot be represented with the large lysimeter. The mass of water pumped out of the mini-lysimeter minus the mass pumped in represents the total (net) seepage. The balance for the lysimeter vessel has a resolution of 1 g, equivalent to a water column of approximately 0.014 mm, while the balance for the external drain water bottle (used to determine seepage) has a resolution of 0.5 g, equivalent to a water column of approximately 0.007 mm. The lysimeter and drain water bottle masses are recorded and stored separately, on a 1-min basis.

Mini-lysimeter processing

For modern lysimeters with high temporal resolution, such as the Rietholzbach mini-lysimeter, it can be assumed that within each recorded time interval ET and precipitation do not co-occur. After the mass change due to seepage has been accounted for, it follows that any remaining decrease of the lysimeter mass must result from ET (ET_{L2}), while any remaining increase must result from precipitation. Using an opto-electric precipitation monitor (Thies, Göttingen), an additional step that can be performed is the separation of precipitation into true meteorological precipitation (rain, hail, sleet, snow, etc.), and condensation (dewfall, fog deposition, frost formation, etc.). If a period of constant mass increase plus/minus 5 min coincides with a greater-than-zero precipitation monitor recording, we interpret it as true precipitation ($P_{true,L2}$). On the other hand, if the precipitation

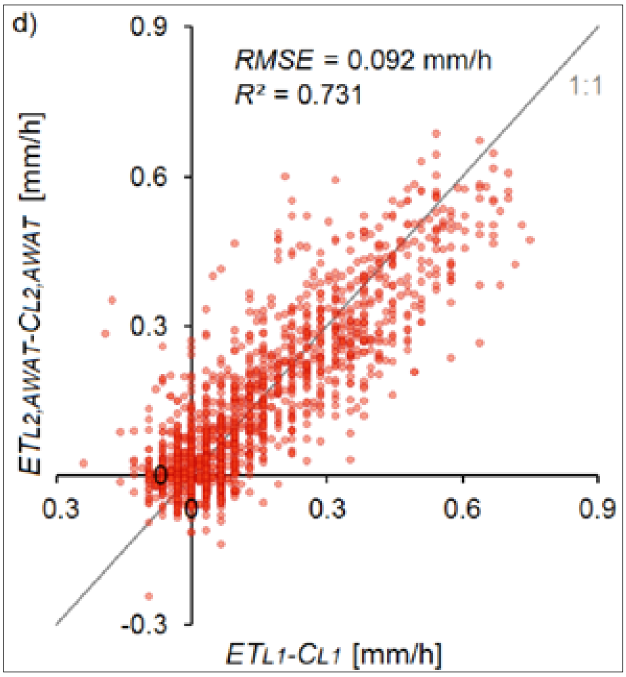

Figure 2: **Mini-lysimeter (L2) vs large lysimeter (L1) hourly evapotranspiration minus condensation ($ET_{L\#}$-$C_{L\#}$) for the AWAT L2 processing approach (May to October, excluding outliers > 2.5 mm/h and times in which any of the L2 records registers true precipitation): Adaptive-Window and Adaptive-Threshold filter ($ET_{L1,AWAT}$-$C_{L1,AWAT}$). The root-mean-square error (RMSE), coefficient of determination (R^2) and the 1:1 line is given for each subplot. Each subplot contains an identical set of 1921 hours. Approximately 46.7% of hours are missing due to data gaps in the precipitation monitor record.**

monitor records nothing, the mass increase is interpreted as condensation (C_{L2}).

To calculate the mini-lysimeter fluxes reliably, it is necessary to first apply some processing to the mass measurements to minimize noise. In this study, we examine the AWAT processing approach introduced by Peters et al. (2014) and assess the resulting records based on their relationship to the large lysimeter and the reference tipping bucket at 1.5 m:

Large lysimeter processing

For the large lysimeter in Büel, the relatively coarse temporal resolution of the mass and seepage recordings (5 min) means that the separation of ET and precipitation in the lysimeter mass record is not feasible. Instead, separate measurements of precipitation from the reference tipping bucket at 1.5 m are input. A disadvantage of this approach is that the tipping bucket resolution is too coarse to represent condensation, leaving it as an additional unknown. The water balance equation for the large lysimeter is thus:

$$ET_{L1} - C_{L1} = P_{true,TB1.5} - (W_{t+1} - W_t) / (\rho_w \pi r^2) - Q. \quad (1)$$

Here, the terms on the right-hand side of the equation represent the measured inputs: $P_{true,TB1.5}$ [mm/h] is true meteorological precipitation from the 1.5-m tipping bucket, Q [mm/h] is seepage from the lysimeter base, and W_t [kg] and W_{t+1} [kg] are the instantaneous lysimeter masses recorded at the beginning and end, respectively, of the hour. The mass measurements are divided by the density of water, ρ_w [kg/m³], and by the surface area of the lysimeter, πr^2 [m²], such that all terms in Eq. 1 have the units of mm/h. The residual term is thus ET minus condensation (ET_{L1}–C_{L1}) [mm/h], which cannot be separated because of the coarse temporal resolution, as stated.

Results and discussion

Analysis of mini-lysimeter processing approach

After applying each of the four mini-lysimeter processing approaches and calculating the fluxes of ET_{L2}, $P_{true,L2}$ and C_{L2} for each, two sets of comparisons were made to assess their performances. The first of these, shown in *Figure 2*, examines the parameter ET_{L2}–C_{L2}, such that the records are comparable to that of the large lysimeter, which is taken as a reference for this analysis. As the large lysimeter record of ET_{L1}–C_{L1} is subject to underestimation due to under-catch with the tipping bucket, only dry times are included here. In each case there is a strong correlation between the two lysimeters, suggesting that no major errors are present. Figure show the ET minus condensation data from the AWAT approach. The total of this record for the examined period is 219.6 mm, and is thus similar to that of the large lysimeter.

The second analysis to assess the mini-lysimeter processing approaches is a comparison of $P_{true,L2}$ versus the corresponding measurements from the 1.5-m tipping bucket (*Figure 3*). The correlation is very high, however the plotted linear regression shows that the reference data are generally lower

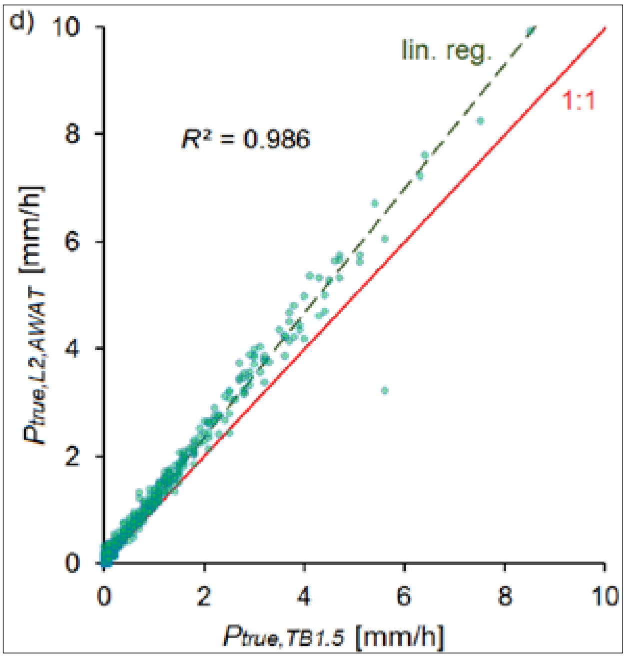

Figure 3: **Hourly 1.5-m tipping-bucket true precipitation ($P_{true,TB1.5}$) vs mini-lysimeter true precipitation ($P_{true,L2}$) for various mini-lysimeter processing approaches (May to October, excluding hours in which none of the L2 records registers true precipitation): Adaptive-Window and Adaptive-Threshold filter ($P_{true,L2,AWAT}$). A linear regression, the R^2 value, and the 1:1 line is given for each subplot. Each subplot contains an identical set of 721 hours.**

than those of the mini-lysimeter. For the period examined, the total tipping bucket precipitation is 488.5 mm. The corresponding mini-lysimeter total is 589.9 mm (+20.8%). Taking the AWAT-processed data as the reference, the difference between the true precipitation totals in *Figure 3* indicates a 1.5-m tipping bucket under-catch of 17.2% (for liquid precipitation). The total for the ground-level tipping bucket (not plotted) over the same period, is 549.0 mm. Hence, even if the instrument is positioned to minimize wind-induced loss, other errors (e.g. related to wetting; WMO 2008) still amount to an under-catch of 6.9%. Using these data, it could be possible to derive a detailed correction scheme for each set of tipping bucket measurements, but that is beyond the scope of this paper.

Optimization of large lysimeter processing

Using the AWAT-processed mini-lysimeter data as a reference, we next sought to improve the processing of the large lysimeter to mitigate the main sources of error described in Section 2.4. Firstly, to reduce the degree of noise in the large lysimeter mass measurements, a retrospectively-applicable moving mean was tested. Historically, this was not applied since even the narrowest possible moving mean width (three measurements) spans a relatively long time interval (10 min), and could potentially result in artificial smoothing of valid signals. *Figure 4* shows a comparison of ET minus condensation from the AWAT-processed mini-lysimeter and the large lysimeter with and without a three-point (10-min) moving mean first applied to the mass measurements. As can be seen from the *RMSE* and R^2 values, the moving mean greatly increases the agreement of the large lysimeter with the reference. Meanwhile, the large lysimeter sum for the period examined (223.6 mm originally, and 223.2 mm with the moving mean) remains similar to that of the reference (219.6 mm). Based on these results, we deduce that the benefit of noise reduction due to the moving mean, outweighs any potential artificial smoothing of valid signal. It should therefore be beneficial to apply this step to the future and (as far back as available) historical data from the Rietholzbach's large lysimeter.

The other source of error we investigate is the underestimation of true precipitation resulting from under-catch with the 1.5-m tipping bucket. In *Figure 5* the large lysimeter record of ET minus condensation with and without various retrospectively-applicable corrections applied is compared to the reference AWAT-processed mini-lysimeter record. Times in which the 1.5-m tipping bucket records 0 mm are plotted in red; times in which it records > 0 mm are plotted in blue. *Figure 5a* shows the regular, uncorrected large lysimeter data. From this it is apparent that the two lysimeters agree relatively well during dry times (as observed in *Figure 2*), yet the large lysimeter generally underestimates ET_{L1}–C_{L1} during precipitation, presumably due to tipping bucket under-catch. This is reflected in the sums for the given period, as the large lysimeter total (207.1 mm) is 15.7% lower than that of the mini-lysimeter (245.7 mm). The final approach to mitigate the effect of tipping bucket under-catch is simply to set the large lysimeter ET minus condensation to zero for hours in which $P_{true,TB1.5} > 0$ (*Figure 5d*). The drawback of this approach is that any valid ET and/or condensation also occurring in these hours will be lost. The resulting ET minus condensation ($ET_{L1,Z}$-$C_{L1,Z}$), however, totals 242.1 mm and is thus only 1.4% lower than that of the mini-lysimeter. Hence, the loss is only minor for the period examined. As this approach also maximizes the agreement between the two lysimeters, it is therefore the best of those investigated,

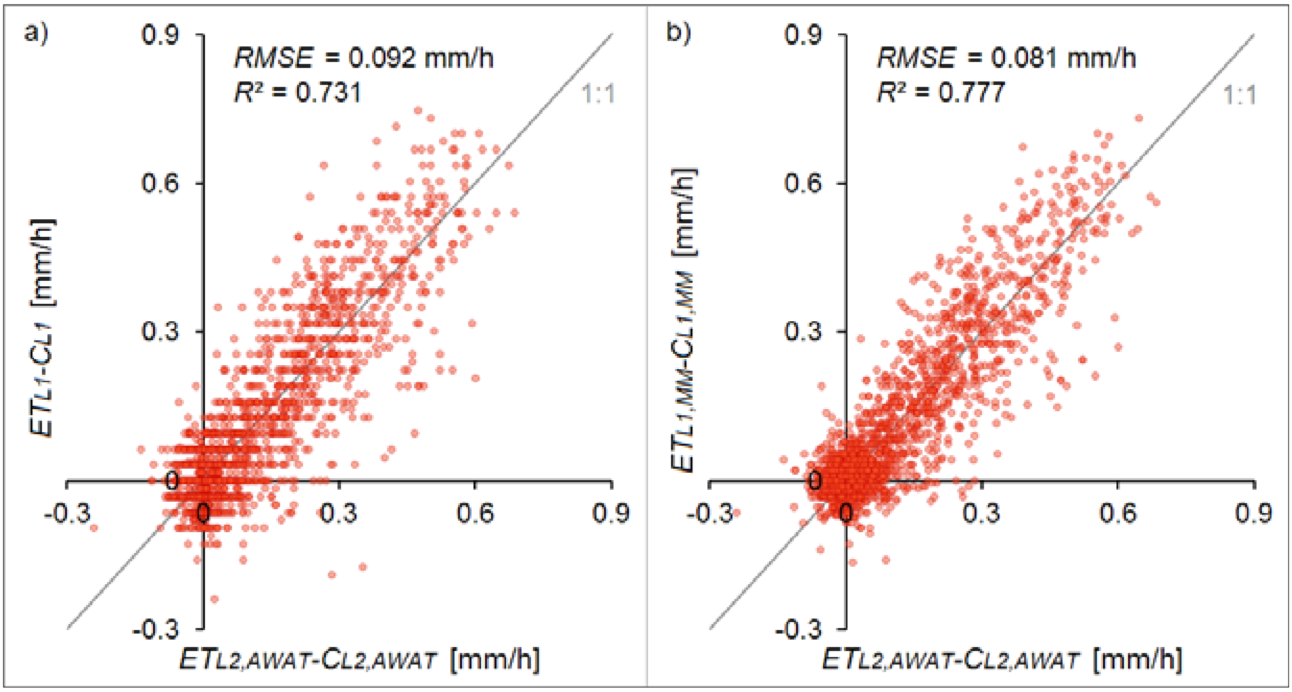

Figure 4: **Large lysimeter (L1) vs Adaptive-Window-and-Adaptive Threshold-filtered mini-lysimeter ($L2_{AWAT}$) hourly evapotranspiration minus condensation ($ET_{L\#}$-$C_{L\#}$; same data set as in Figure 2): a) without any additional L1 processing, b) with a three-measurement (10-min) moving mean first applied to the large lysimeter mass measurements ($ET_{L1,MM}$-$C_{L2,MM}$). The root-mean-square error (RMSE), coefficient of determination (R²) and the 1:1 line is given for each subplot.**

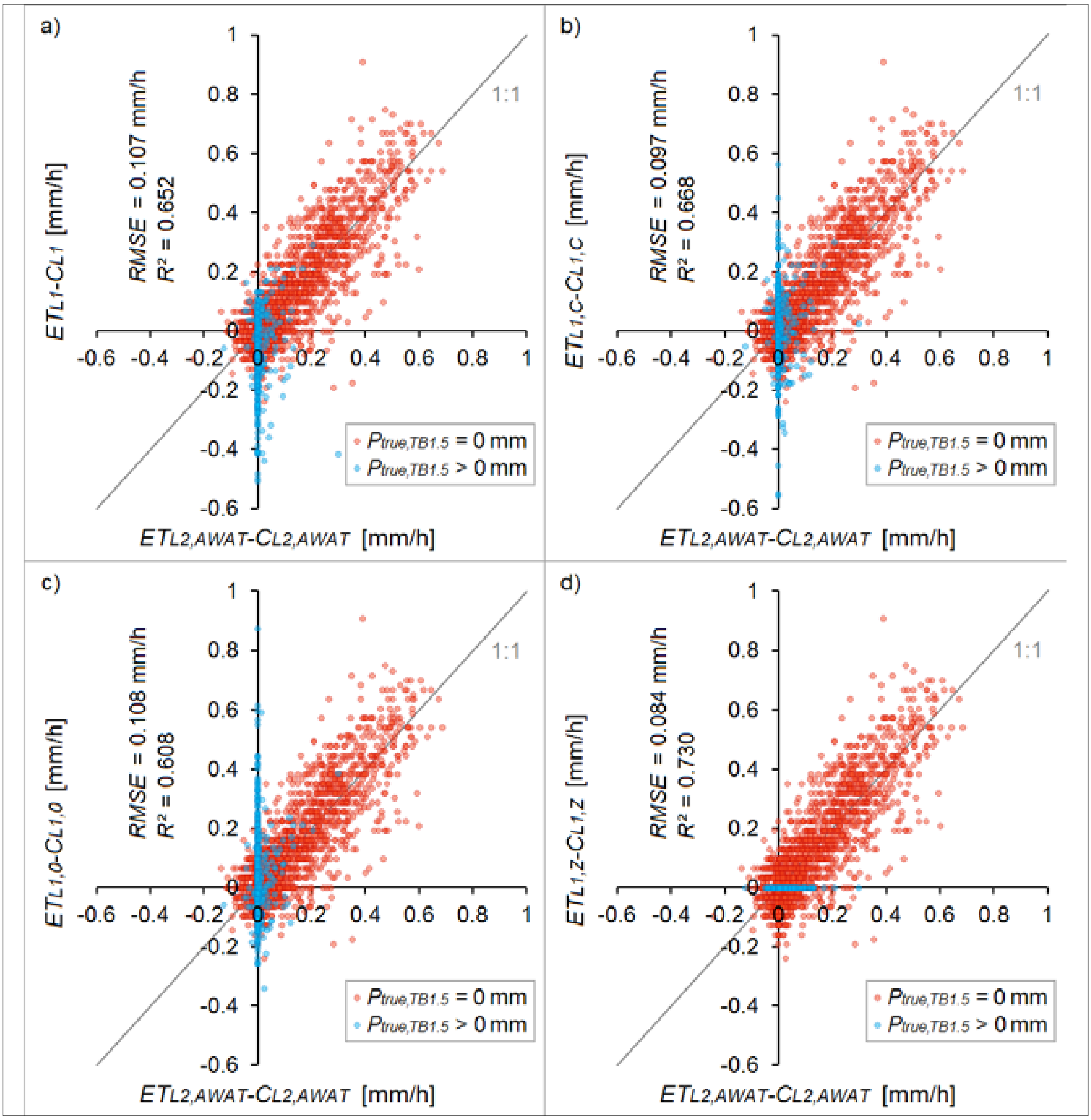

Figure 5: **Large lysimeter (L1) vs Adaptive-Window-and-Adaptive Threshold-filtered mini-lysimeter ($L2_{AWAT}$) hourly evapotranspiration minus condensation ($ET_{L\#}$-$C_{L\#}$) for various tipping-bucket-related, alternative L1 processing approaches (May to October, including times of true precipitation):) ET_{L1}-C_{L1}: regular L1 processing, b)$ET_{L1,C}$-$C_{L1,C}$: 1.5-m tipping bucket recordings ($P_{true,TB1.5}$) multiplied by a constant corction factor, such that the resulting L1 ET-C total for the examined period equals that of L2AWAT, c) $ET_{L1,0}$-$C_{L1,0}$: ET-C calculated using the ground-level tipping bucket recordings, d) $ET_{L1,Z}$-$C_{L1,Z}$: ET-C set to zero for hours with $P_{true,TB1.5} > 0$ mm. The root-mean-square error (RMSE), coefficeint of determination (R^2) and the 1:1 line is given for each subplot. Each subplot contains an identical set of 2738 hours. Approximately 46.7% of hours are missing due to data gaps in the precipitation monitor record.**

and based on these findings it would be beneficial if applied to the historical and future large lysimeter data from the Rietholzbach. It should be noted, however, that Hirschi et al. (2016) found the amount of ET occurring during times of precipitation to vary considerably from year to year at the same site. A longer analysis is therefore advised to ensure the suitability of this approach.

Comparison of lysimeter mass increases during precipitation

As seen in *Figure 5c*, the large lysimeter record of ET minus condensation calculated with the ground-level tipping bucket is generally higher than that of the reference mini-lysimeter during times of precipitation. This could arise if the ground-level tipping bucket experienced an over-catch of precipitation, although we have already found that this is not the case (see Section 3.1). To investigate if this behavior is related to the precipitation catch of the lysimeters themselves, the seepage-corrected mass increases of each lysimeter per unit area (expressed in mm/h) were compared to the set of greater-than-zero ground-level tipping bucket recordings. This was done for hours in which the AWAT-processed mini-lysimeter ET and condensation both equal zero, such that any overall differences between the records, in theory, must result from differences in true precipitation catch. We found that the mass increases of the large lysimeter per unit area are generally much lower than those of the mini-lysimeter. This implies either under-catch of true precipitation with the large lysimeter and/or over-catch with the mini-lysimeter. As we have already observed that the ground-level tipping bucket recordings are underestimated, we would expect each set of lysimeter mass increase to be higher than true precipitation. However, as the large lysimeter mass increases lie substantially below the amount of precipitation (not shown), we attribute the observed difference between the lysimeters to an under-catch of true precipitation with the large lysimeter. Assuming the mini-lysimeter data to be correct, the sums of the mass increases indicate the magnitude of this under-catch to be 11.1% (for liquid precipitation).

Conclusions

In this study, we examined the measurements from a large free-drainage weighing lysimeter and a state-of-the-art mini-lysimeter with a pump-controlled lower boundary, installed in the Rietholzbach catchment in northeastern Switzerland. Taking the large lysimeter and the 1.5-m tipping bucket as references, the AWAT processing of the mini-lysimeter data were investigated through examination of the resulting ET_{L2}-C_{L2}, and $P_{true,L2}$ records. This was chosen as the reference mini-lysimeter processing approach. Using the AWAT-filtered mini-lysimeter data, we then investigated a number of additional, retrospectively-applicable processing steps for the large lysimeter, intended to mitigate the main sources of error for this instrument. Those found to be most beneficial were the application of a three-point (10-min) moving mean to the mass measurements, and the setting-to-zero of ET minus condensation for hours in which the 1.5-m tipping bucket records precipitation. These steps could also be beneficial for lysimeters with similarly coarse resolution at other sites. While investigating these additional processing steps, it was discovered that the large lysimeter experiences a previously unknown under-catch of true precipitation, estimated to be 11.1% for liquid precipitation. This could be related to the slight protrusion of this instrument above the surroundings. A comparison of daily seepage from each lysimeter revealed generally lower values for the large lysimeter, probably reflecting the reduced input of water due to the aforementioned under-catch. On the other hand, ET from the large lysimeter was not found to be affected by this, as the record of ET_{L1}-C_{L1} approximately equals that of the mini-lysimeter in the absence of tipping bucket errors.

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