# Insights into rainfall undercatch for differing raingauge rim heights

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## ABSTRACT

The measurement of rainfall has a long history, but despite its apparent simplicity it is difficult to quantify accurately. The common installation of raingauges with rims above the ground surface results in a difference between the rainfall caught and the amount reaching ground level, termed undercatch. The UK standard installation of raingauges is for their rim to be sited at 0.305 m above the ground; however, the use of weighing gauges installed at a minimum rim height of 1 m has increased in recent years. The installation of these weighing raingauges raises complex questions of homogeneity in rainfall data across space and time. Here, we investigate the impact of these changes using field trials of commonly deployed UK raingauges at a site in south-east England. This paper discusses the results of the trial, exploring the variation in and potential drivers of undercatch with differing gauge sitings. With varying standards for gauge heights around the world and new rainfall measurement technologies coming to the market all the time, improved understanding of undercatch is needed to inform evolving operational practices and explore the possibility of developing catch correction algorithms to remove arising inhomogeneity in precipitation datasets.

**Key words** | hydrometry, precipitation, rainfall, raingauge, undercatch

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## INTRODUCTION

Accurate measurement of rainfall amount is crucial for many areas of hydrology, including water balance studies, flow forecasting, modelling and water resource assessments (Tian *et al.* 2007; Looper *et al.* 2012; Stisen *et al.* 2012). Rainfall has been measured since as early as the fourth century and there are currently many different types of gauge in use around the world, although manual storage gauges read by observers on a daily or monthly basis form a large part of the UK's long-established rainfall observational network (Strangeways 2010). This network is augmented with automatic recording gauges which are used to measure rainfall at a finer temporal resolution, essential for uses such as flood risk modelling and hazard warning systems (Tapiador *et al.* 2012). However, despite a long history of observations in the UK and around the world, it is widely acknowledged that there are many errors (both random and systematic) encountered when measuring rainfall whether manual or automatic gauges are used.

Irrespective of gauge type, a common issue in the measurement of rainfall is wind-induced undercatch where, due to the deformation of wind and increased turbulence above the gauge rim, raindrops are deflected away from the collecting orifice meaning less rain is recorded in a gauge mounted above the ground than would reach ground level (Rodda & Dixon 2012). This undercatch effect has been investigated extensively by field intercomparisons (e.g. Sevruk *et al.* 2009; Chubb *et al.* 2015; Pollock *et al.* 2018) and computational fluid dynamics modelling



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(e.g. Nespor & Sevruk 1999; Colli *et al.* 2018). In addition, accuracy is found to be affected by rainfall intensity, most notably in tipping-bucket gauges where counting errors have been observed (Molini *et al.* 2005). For the users of precipitation data, understanding the impact of this issue on the homogeneity of records across space and time is made more complex due to variations between different types of gauges and the way in which they are sited.

While there are a set number of gauge types available (Strangeways 2010), many of which have been subject to extensive intercomparison studies (e.g. Lanza & Vuerich 2009), there is a significant variation in the way that gauges are installed around the world. The World Meteorological Organization (WMO) recommends that the height of the gauge rim should be as low as possible but high enough to prevent splashing in from the ground surface (WMO 2008). A number of options exist to minimise the impact of increasing wind velocities with gauge height, including installing a shield to reduce the velocity around the gauge (Benning & Yang 2005), installing a turf wall (Essery & Wilcock 1991) or installing a gauge of a more aerodynamic shape (Strangeways 2004; Sieck *et al.* 2007; Colli *et al.* 2018). However, the most effective approach is to install a gauge within a pit to ensure the rim is at ground level preventing the body of the gauge from creating an obstacle to the wind (Rodda 1968). Extensive trials took place in the 1960s in Wallingford (Oxfordshire, UK) to assess the impact of the shape and size of pit grids, and now a European standard exists for the design of reference raingauge pits (CEN 2010) which can be used to evaluate wind effects or to conduct comparison against other reference raingauges. The installation of gauges in pits to create a reference rainfall series means that the rainfall recorded in a gauge above the ground surface may be corrected to the value reaching the surface (Allerup & Madsen 1980; Essery & Wilcock 1991; Mekonnen *et al.* 2015; Kochendorfer *et al.* 2017).

Tipping-bucket raingauges (TBRs) are one of the most popular automatic gauges in use globally but have many issues (Habib *et al.* 2001; Ciach 2003; Michaelides *et al.* 2009). TBRs are subject to random errors (due to clogging/blockages or mechanical failures (Sevruk 1996; Upton & Rahimi 2003)) and systematic errors (e.g. counting errors where rainfall is underestimated during high-intensity events as water is lost in the tipping movement of the buckets (Molini *et al.* 2005)). TBRs (and manual storage gauges) are also particularly unreliable in measuring solid precipitation, as it has to melt before it is recorded (Savina *et al.* 2012). Other technology exists in the form of weighing raingauges (WRGs), and although they are not deployed widely (Tapiador *et al.* 2012), their use is increasing globally (e.g. Sevruk & Chvíla 2005; Gray & Toucher 2019). Compared with TBRs, they can more easily provide a greater sensitivity of precipitation measurement (e.g. to 0.01 mm) as no moving buckets are required, they can minimise evaporation and wetting losses due to the lack of a funnel and have demonstrated improved snow measurement capabilities in some field trials (when heated due to reduced evaporation losses from a smaller heated area (e.g. Savina *et al.* 2012)).

For many years, the UK raingauge network comprised a mixture of storage and tipping-bucket gauges. However, due to the advantages mentioned above and the reduced maintenance and calibration requirements shown by a trial conducted at two sites in Scotland and Wales (Grust & Stewart 2012), WRGs have, in many cases, been deployed as replacements for TBRs in the UK since 2013. The Ott Pluvio gauge has been widely chosen as the WRG to replace TBRs and have been installed with their rims 1 m above the ground surface compared with the 0.305 m commonly used for TBRs and manual storage gauges in the UK.

Observation networks have always evolved as measurement practices and technologies are developed and changes in gauge type and/or siting such as that seen in the UK in recent years. However, these changes can potentially create unknown inhomogeneity in time series without extensive periods of dual running and/or specific intercomparison studies (Sevruk 1996; Savina *et al.* 2012). While comparisons between the different models of raingauge currently deployed in the UK have been conducted by others (Colli *et al.* 2018), and this study does not seek to repeat such work, the difference in shape and rim height between gauges raises the potential for increased amounts of wind-induced undercatch by the newly deployed WRGs. In this study, we explore undercatch across the different UK dominant raingauge types and common sitings and attempt to isolate the impact of wind-induced errors by comparing observations from each gauge with ground-level installations of the same make and model.

## STUDY DESIGN

### Site location

The meteorological station at the Centre for Ecology & Hydrology in Wallingford, Oxfordshire (UK) has been in operation since 1962. The site is located on the floodplain of the River Thames in south-east England at a height of 47 m above sea level. The wind direction is dominated by a west/south-west direction, and the mean annual precipitation (calculated using 1969–2018 manual daily pit gauge data) is 611 mm. The site contains equipment for 09:00 GMT daily manual observations of temperature, wind, precipitation and sunshine and forms part of the UK Climatological Observation Network for the UK Met Office (https://www.metoffice.gov.uk/public/weather/climate-network/#?tab=climateNetwork) (ID 5558). These measurements are replicated by an Automatic Weather Station (AWS) in the same compound, recording data at 15-min intervals.

### Instrumentation

For the purpose of this study, the station contains seven raingauges (Figure 1) – two UK Met Office MK2 daily storage gauges, two Casella tipping-bucket gauges and three Ott Pluvio weighing gauges (Table 1). One gauge of each type is installed at the UK standard 0.305 m rim height and one Ott Pluvio at 1 m, reflecting the common siting used across the UK for such gauges in recent years. Each gauge is spaced to minimise the aerodynamic effects of each other, and no gauge is sited in a way which convenes the 26° exposure angle stated in the British Standard (BS7843-2:2012). Both TBRs have 0.2 mm buckets and have been calibrated throughout the operating period using volumetric calibration to an intensity of 10 mm/h. The Ott Pluvio gauges were calibrated and checked for drift in weighing capability (using known weights) throughout and no adjustments were required.

One gauge of each type is installed with a rim height at ground level (shown with an * in Table 1 and Figure 1) by siting them in separate 1.4 m × 1.4 m pits, 0.305 m deep (for storage and tipping-bucket gauges) and 1 m deep (for weighing gauges), with a 1.2 m × 1.2 m anti-splash metal grid on the surface, complying with the European Standards (CEN 2010) and WMO recommendations (WMO 2008). All analysis for gauges installed with their rim above ground level was done by comparison with the relevant reference pit gauges of the same types. This set-up removes the influence of changing gauge technologies from the trial and isolates the effect of undercatch. Wind speed is recorded by a cup anemometer mounted at 2 m.

### Data preparation

The data and results presented here reflect the period where all three gauge types were in operation (August 2015–August 2018). All sub-daily rainfall data were quality controlled using the other gauge heights and types. Records identified as being anomalous (e.g. due to the Pluvio incorrectly recording rainfall during high temperatures when the collecting bucket is empty) were removed. Daily and monthly totals were then checked for any large discrepancies, but none were found. Any periods of missing data (e.g. due to instrument calibration or telemetry failure) were checked against other gauge types. For the study period, there were four large (>24-h) missing data periods, two of which were within periods of no rainfall and two coincided with small (<1 mm) daily rainfall totals. Therefore, with minimal impact of missing data on the analysis, all data were included. Daily and monthly totals were calculated over the UK standard 09:00–09:00 hydrological day. Seasonal figures were calculated for UK winter (December–February), spring (March–May), summer (June–August) and autumn (September–November) using monthly totals.

In order to investigate the potential driving factors behind any undercatch, an event dataset was created using the 15-min resolution reference Pluvio gauge (0.000 m) data against which the 0.305 and 1 m Pluvio data could be compared. Although the Pluvio provides measurements at 1-min resolution this was not used in this study, as operationally within the UK 15-min data are used for reporting and analysis. In addition, wind speed measurements from the Wallingford station were only available at 15-min intervals for direct comparison with the rainfall. The definition of rainfall event can vary depending on the purpose of a given study, but events are generally based on a period of accumulated rainfall above a set threshold

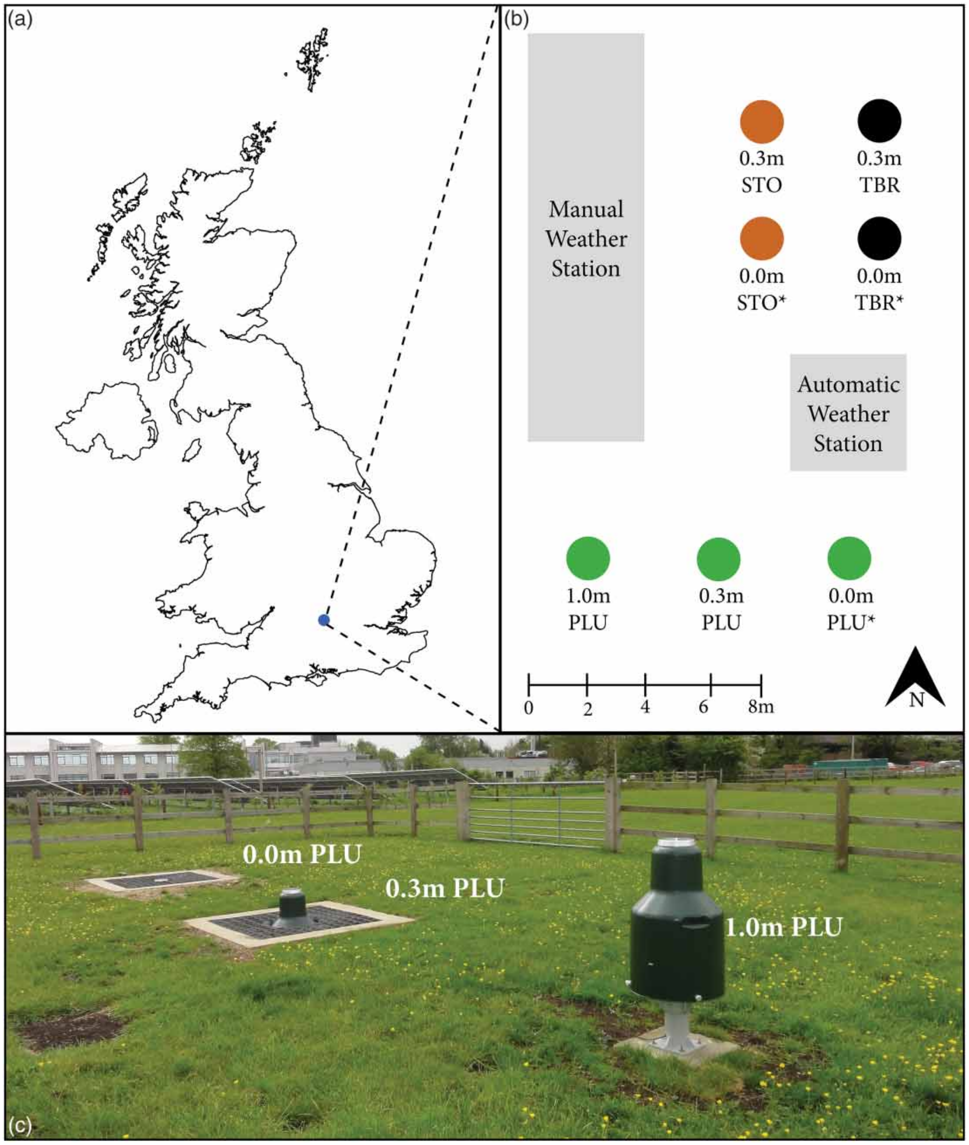


**Figure 1** | (a) Location of meteorological station at the Centre for Ecology & Hydrology in Wallingord (UK); (b) site plan with reference gauges used in the study shown with an * (gauge size is not to scale shown) and (c) photograph of Ott Pluvio installation.

separated by a given period of time. This period is known as the 'minimum inter-event time' (MIT) and in a review by Dunkerley (2008) covering a wide range of geographical locations lengths of between 0.25 and 24 h were found to be in use, with the majority between 6 and 8 h. In southern England, rainfall events are a mixture of frontal events (long MIT) and convective storms (small MIT) (https://www.metoffice.gov.uk/climate/uk/regional-climates/so#rainfall). For this study, event datasets were produced and analysed for 1-, 2-, 3- and 4-h MITs. A 3-h MIT was chosen, as it was found to provide a good balance to include both convective and frontal events. In addition, an accumulation threshold of 1 mm (recorded in each of the three weighing gauges) was used, which generated a dataset of 288 events. Snowfall was present in six of these events, and as snow only represents a small proportion of the dataset and the climatology of the site is such that snowfall is rarely observed, these events were excluded creating a dataset of 282 events for analysis. For each event, the characteristics listed in Table 2 and the percentage catch for each Pluvio

**Table 1** | Metadata (gauge type, sitings height, the temporal resolution of data collected and date of installation) of the raingauges used in this study

| Abbreviation | Gauge type | Gauge rim height (m) | Temporal resolution | Year of installation |
|---|---|---|---|---|
| 0.0 m STO* | Storage | 0.000 | Daily | 1969 |
| 0.3 m STO | Storage | 0.305 | Daily | 1962 |
| 0.0 m TBR* | Tipping bucket | 0.000 | 15 min | 2002 |
| 0.3 m TBR | Tipping bucket | 0.305 | 15 min | 2011 |
| 0.0 m PLU* | Weighing | 0.000 | 15 min | 2015 |
| 0.3 m PLU | Weighing | 0.305 | 15 min | 2015 |
| 1.0 m PLU | Weighing | 1.000 | 15 min | 2015 |

*The reference gauges for each type.

**Table 2** | Metadata for characteristics derived from the Pluvio event dataset – name, unit, minimum, mean and maximum recorded in the 0.0 m PLU

| Event characteristic | Unit | Minimum | Mean | Maximum |
|---|---|---|---|---|
| Duration | h | 0.50 | 6.40 | 36.25 |
| Rainfall total | mm | 1.06 | 5.82 | 41.97 |
| Average wind speed (when raining) | m/s | 0.12 | 2.22 | 6.30 |
| Average event intensity (rainfall total divided by event duration) | mm/h | 0.33 | 1.54 | 10.99 |

installed above the ground compared with the reference gauge were calculated.

## RESULTS

### Monthly undercatch analysis

To assess the degree to which undercatch is observed for the different gauges, the percentage catch for each month was calculated using the monthly totals from the gauges mounted at 0.305 m (for PLU, TBR and STO) and 1.0 m (for PLU) and the reference gauge of each type mounted at 0.0 m. Figure 2 shows the clear evidence of undercatch, with the value in each month registering below the 100% reference rainfall line. Over the study period, the gauges mounted at 0.305 m recorded an average of 93.7% (0.3 m PLU), 94.4% (0.3 m TBR) and 94.7% (0.3 m STO) of the rainfall collected in the equivalent gauge installed at 0.0 m

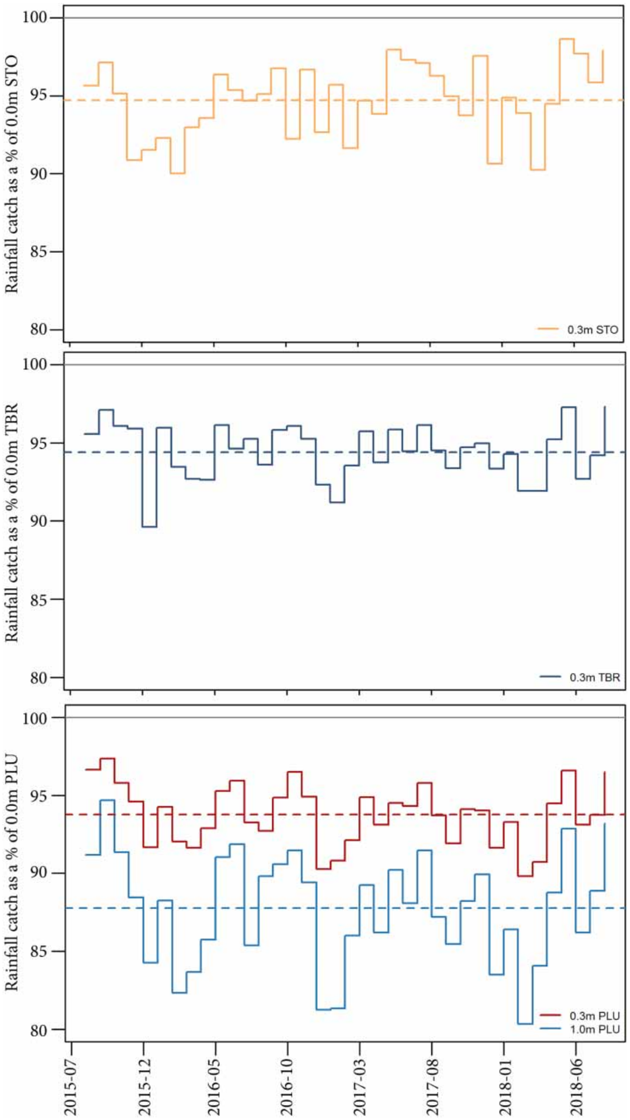


**Figure 2** | Monthly undercatch in each raingauge, calculated as a percentage of the rainfall recorded in the reference gauge of that type (mounted at 0.0 m).

(i.e. a 5.3–6.3% undercatch). Significant variation was observed over the study period, ranging from a maximum monthly undercatch of 10.4% (December 2015, 0.3 m TBR) to a minimum of 1.4% (May 2018, 0.3 m STO). Notable variation was observed between the seasons (Figure 3), with the largest amounts of undercatch in the winter and smallest amounts in summer (0.3 m PLU, 0.3 m TBR)/autumn (0.3 m STO).

When compared with the 0.305 m gauges, increased amounts of undercatch were observed for the Ott Pluvio

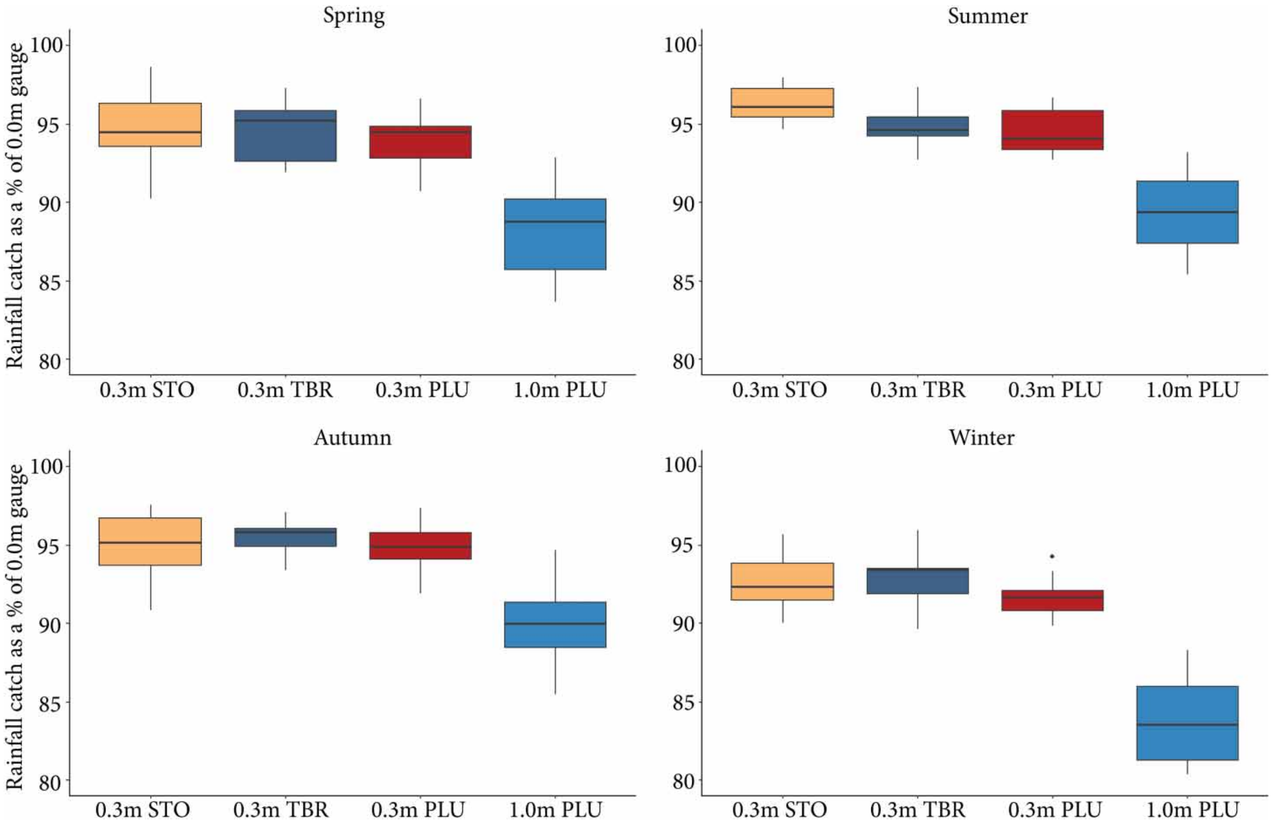


**Figure 3** | Seasonal variation in undercatch recorded in each gauge as a percentage of the corresponding reference gauge.

with its rim mounted at a height of 1.0 m (Figure 2). Over the study period, the 1.0 m PLU recorded on average 87.3% of the rainfall recorded in the 0.0 m PLU, an undercatch of 12.7% – double that of the undercatch recorded in the 0.3 m PLU. There was also a wider range of values of monthly undercatch shown in the 1.0 m PLU – a maximum monthly undercatch of 19.6% (February 2018) and a minimum of 5.5% (September 2015). Similarly to the 0.305 m mounted gauges, the smallest amount of undercatch occurred in the summer and the largest in winter (Figure 3).

## Event-based analysis

Using the dataset of 282 events, there is evidence of positive relationships between wind speed and undercatch for both Pluvio gauges (Figure 4(a)) which, while statistically significant ($p < 0.0001$), are weak with a large amount of scatter seen in the data. At low wind speeds (<1 m/s), the difference in undercatch between the gauges is smaller (although the 1.0 m PLU exhibits a wide range of undercatch during events) than at high wind speeds (>4 m/s), where there is a large difference in undercatch experienced between the gauges (Figure 4(b)).

A weak negative relationship was observed between undercatch and event average intensity (Figure 5(a)) but again, while statistically significant ($p < 0.001$), a large amount of scatter was seen, particularly at low intensities. The differences between the two gauges were more pronounced at lower intensities (Figure 5(b)); however, it should be noted that the dataset is highly skewed towards low-intensity events due to the climatology of the site (78% of the 282 events have an event average intensity of <2 mm/h) meaning that the effects of higher intensity events could not be well assessed.

The analysis presented in Figures 4 and 5 is based on the average intensity and wind speed of each event and when the event dataset was analysed using maximum data, a similar relationship was found. In order to explore the data further, four events were chosen for more

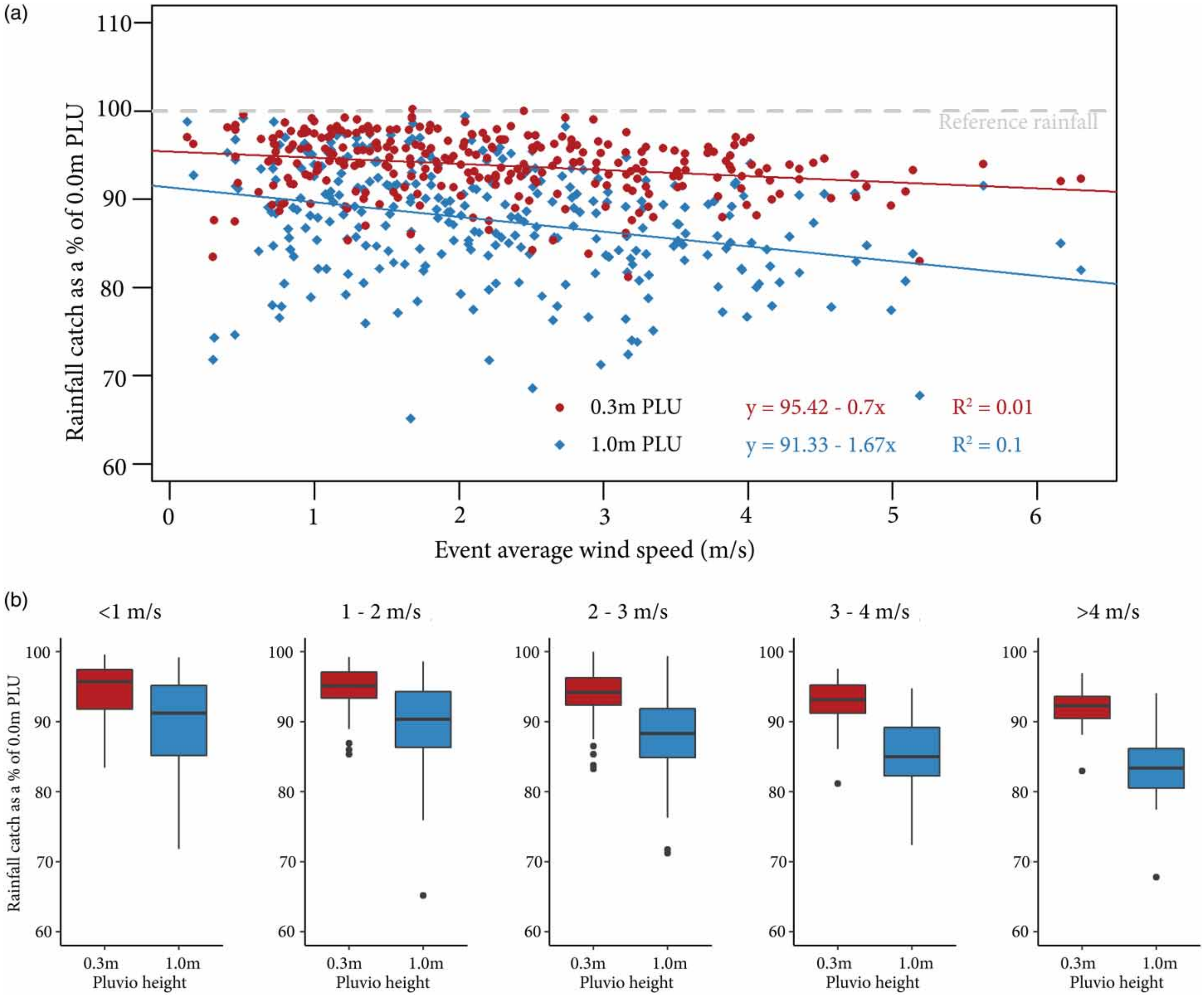


**Figure 4** | Comparison between wind speed and undercatch recorded in 0.3 and 1.0 m PLU referenced to the 0.0 m PLU for all events (a) and subsets of wind speed (b).

detailed analysis. There was variation in undercatch observed during the events; however, there was no obvious pattern and, therefore, only the variation in wind speed and intensity are shown in Figure 6. The two low average intensity (<2 mm/h) events shown in Figure 6(a) and 6(b) exhibit large amounts of undercatch – 15–20% undercatch in the 0.3 m PLU and 25–30% undercatch in the 1.0 m PLU. In contrast, the two examples of high average intensity (>4 mm/h) events shown in Figure 6(c) and 6(d) exhibit small amounts of undercatch – 3–4% undercatch in the 0.3 m PLU and 5–8% undercatch in the 1.0 m PLU. Figure 6(d) shows the highest intensity event within the dataset (11 mm/h) which cause some localised surface water flooding in Wallingford. Within this event, it is evident that during the higher intensity period at the beginning where undercatch would be expected to be small (based on Figure 5), the concurrent high wind speed acts to increase the amount of undercatch (up to 8% in the 1.0 m PLU) and drops later on in the event (to only 1.5% in the 1.0 m PLU).

## DISCUSSION

The results presented here for the three gauges mounted at 0.305 m compared with a reference pit gauge are

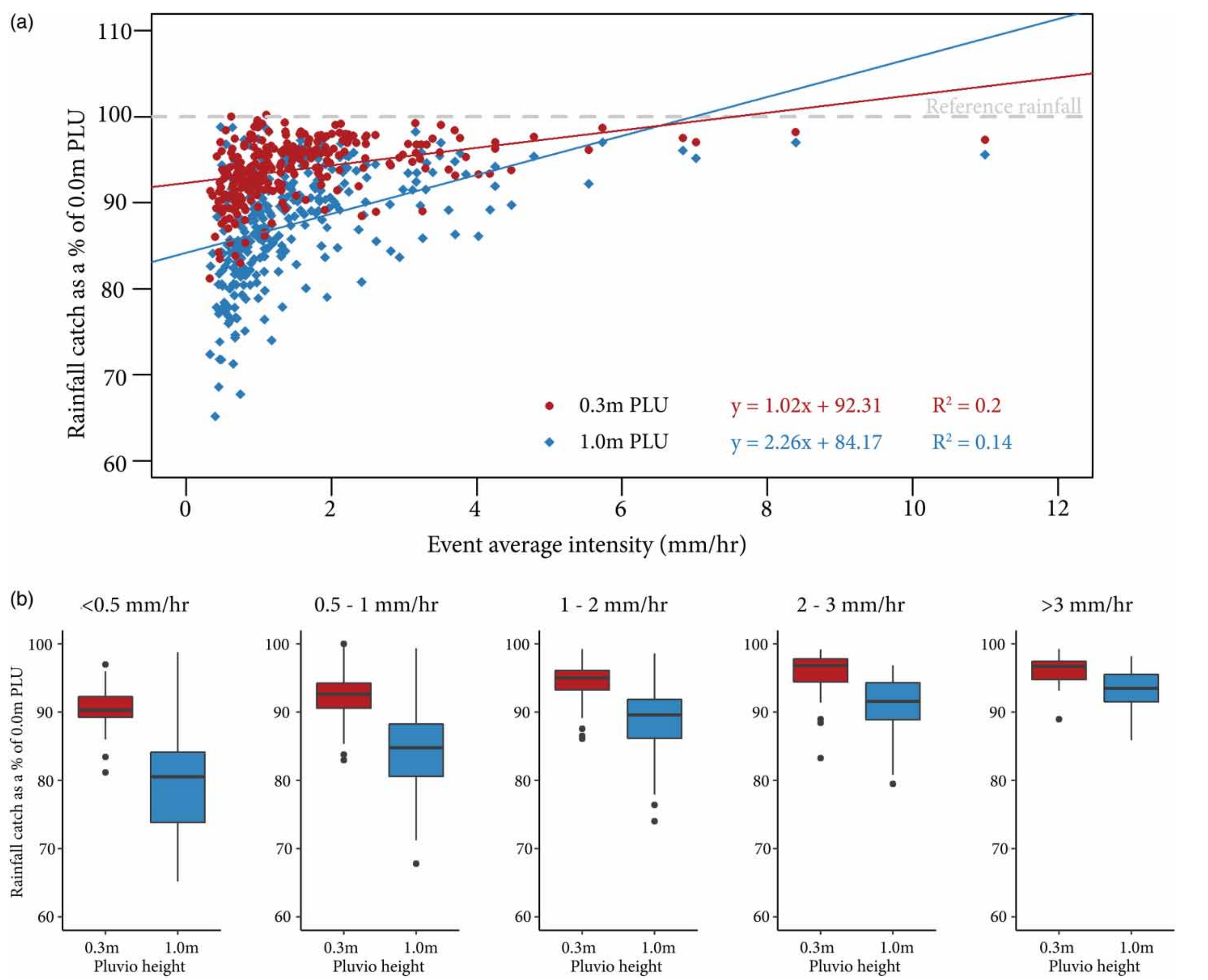


**Figure 5** | Comparison between event average intensity and undercatch recorded in 0.3 and 1.0 m PLU referenced to the 0.0 m PLU for all events (a) and subsets of intensity (b).

comparable with previous studies at Wallingford published in Rodda (1968) and Rodda & Dixon (2012), which showed an average undercatch of 6.6% and 5.4%, respectively, compared with 5.3–6.3% reported here. The results here also agree with Rodda (1968) in terms of seasonality, with a maximum undercatch in winter and a minimum in summer, although there was variation between gauges. Similar values of undercatch have been presented in other studies within the UK, for example, Essery & Wilcock (1991) found an average of 5% undercatch between an exposed and pit storage gauge in Northern Ireland, although with temporal variation; and internationally, for example, Sieck *et al.* (2007) found 2–12% undercatch from gauges installed above the ground (at varying heights up to 0.5 m) in the USA.

All previous work published from Wallingford uses daily data from storage gauges, whereas this is the first presentation of data from automatic gauges of the type commonly installed across the current UK precipitation monitoring network. The broad similarity in undercatch between gauges of different types when sited at the UK standard 0.305 m is encouraging, suggesting that changing gauge types have little impact on wind-induced errors where the rim height is maintained at a constant. It should be noted however that, as stated in the Study Design section, the

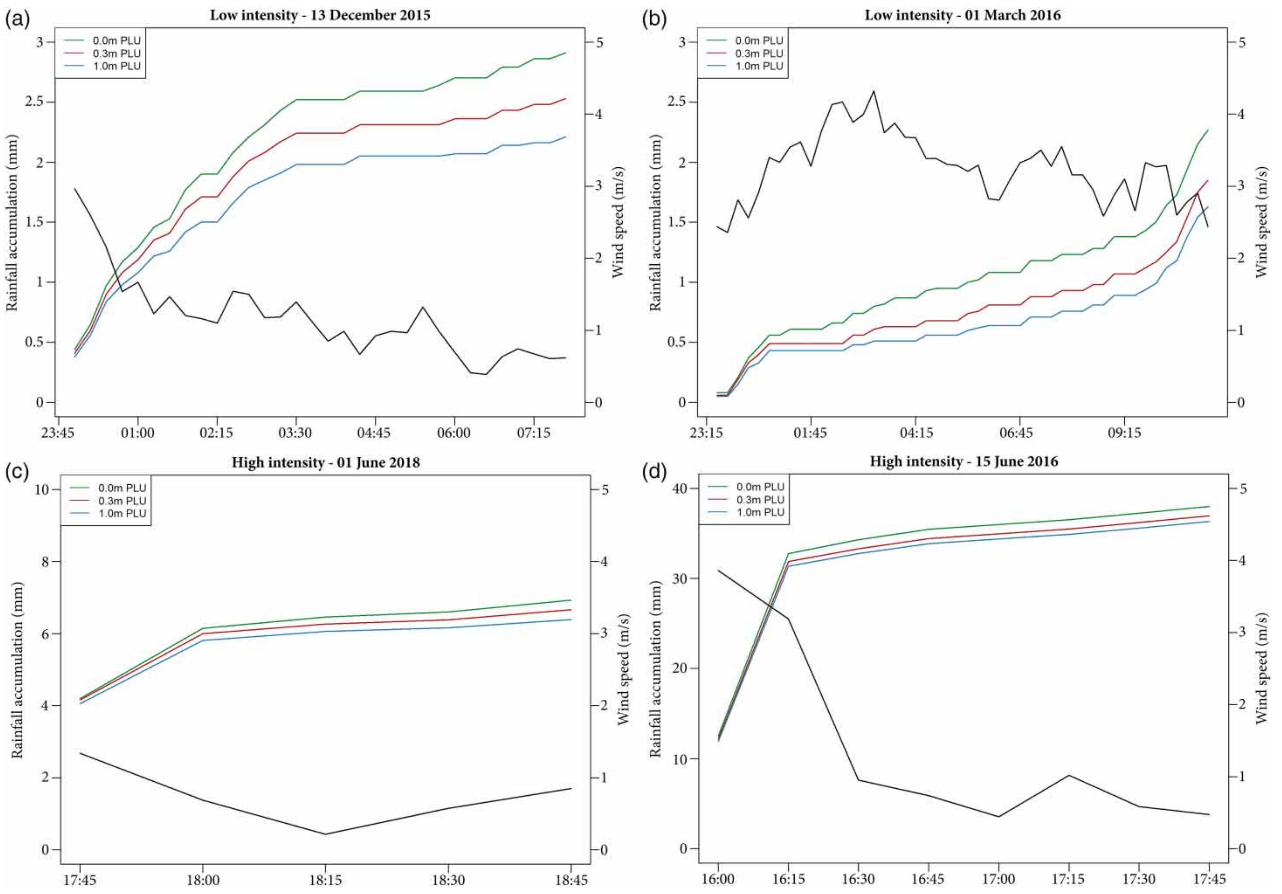


**Figure 6** | Event rainfall accumulation and wind speed for two low event average intensity events ((a) and (b)) and two high event average intensity events ((c) and (d)).

effect of changing gauge type on other errors and uncertainties was isolated from this trial and thus this paper makes no comment on these.

The benefits of weighing gauges over TBRs have been well documented and have been a major driver in the installation of the gauges in the UK operational network. However, Pluvio gauges at a height of 1 m have generally replaced TBRs at 0.305 m, with the increase in height creating a larger disturbance of the surrounding airflow and installation in an area of higher wind speeds due to the boundary layer effect. In a computational fluid dynamics assessment, Colli *et al.* (2018) concluded 'the "chimney shaped" Ott Pluvio provides the least favourable aerodynamic performance when confronted by an airflow'. In this study, the installation of the Pluvio at the standard height of 1 m almost doubled the amount of undercatch on average compared with the same gauge installed at a height of 0.305 m (referenced to the pit gauge). The average of 12.7% (max 19.6%) undercatch for the Pluvio mounted at 1 m represents a substantial increase over that observed for lower gauges. The magnitude of the difference between the 0.305 and 1 m Pluvio gauges was generally more pronounced at times of higher wind speed and for lower intensity events. This finding is particularly notable given the lowland location of the Wallingford site. This percentage is comparable with gauges installed at a lower height at upland sites (e.g. 11.7% at a 0.5 m mounted gauge in Scotland (Pollock *et al.* 2018)) suggesting that even higher undercatch could be expected from 1 m gauges in upland locations. As weighing gauges could present the largest 'operational' benefits in upland areas where remote access means that reduced maintenance visits are a particular advantage (Grust & Stewart 2012), further investigation of undercatch at such sites is required.

The results presented here suggest that where the gauge rim height is maintained at a constant height, the change in gauge type from the daily storage gauges (which initially made up most of the UK observation network) to TBRs and more recently Pluvio WRGs does not significantly impact upon the wind-induced errors. This is perhaps in part because the shape of a Pluvio is not dissimilar to a conventional cylindrical-shaped TBR when mounted at 0.305 m (Figure 1). However, in the context of the UK network where a standard rim height of 0.305 m has been in use for over 100 years, the change to siting gauges with a rim height of 1 m may introduce significant inhomogeneity into rainfall records.

The lowering of rim heights on WRGs presents design challenges as they commonly need to incorporate a large collecting vessel to maximise the amount of rainfall they can catch between being emptied (either manually or via evaporation). One solution is, therefore, to install such gauges in pits, but it is acknowledged that the construction and maintenance of these for every gauge in the national network is unlikely to be practical. Therefore, in order to overcome this and yield usable data from a growing network of Pluvios in the UK operational network, correction factors need to be developed to adjust rainfall totals recorded at specific heights to equivalent rainfall totals recorded at the standard height – and preferably to ground level for purposes such as hydrology where the amount of precipitation reaching the ground is of interest. Previous studies involving the development of a correction factor have used linear regression (e.g. Essery & Wilcock 1991; Benning & Yang 2005) although only using relatively simple approaches applied at broad timescales. The relationships found in this study, although similar in direction to those of Seibert & Morén (1999) and Chvíla *et al.* (2005), are based on a short-length dataset with a large amount of scatter and a skewed intensity variable, therefore the development of correction factors is not recommended based on the data presented here.

For many applications, dynamic correction of data at a finer time-step would be essential as an investigation into the drivers of undercatch in this study shows marked variations within events (Figure 6). In order to further understand this relationship, higher temporal resolution wind speed and rainfall observations are needed. Anemometers installed at the rim height of each Pluvio with wind speed data delivered at a 1-min time resolution were not available during the study but have since been added to the next phase of the field trial to further develop an understanding of the relationship between wind speed and undercatch. The advantages of increased time resolution of rainfall measurements have been shown by Chvíla *et al.* (2005), but Nystuen *et al.* (1996) found increased noise in 1-min data from weighing gauges, which may make further investigations into undercatch more challenging.

Even with a more detailed understanding of the drivers of undercatch from higher resolution data, due to the variable nature of the UK climate (Parry *et al.* 2013), any correction factor that could be developed using the results of this study would be site-specific. An early attempt to understand this spatial variation in undercatch is presented in Rodda & Smith (1986) for the UK (1–16% undercatch) and Sevruk & Hamon (1984) internationally (0–30% undercatch). In a more recent study, Pollock *et al.* (2018) compared undercatch between a lowland site in England and an upland site in Scotland which varied between 3.4 and 11.2%, respectively, due to different wind velocities during events. It may be possible to develop spatially variable corrections based on site climatologies, although this is complicated by the lower density of the meteorological monitoring network in the UK compared with the raingauge network. Ultimately, however, a detailed understanding of the impact of wind-induced errors on rainfall observations across the UK is unlikely to be possible without the development of a network of reference gauges installed at ground level alongside gauges at other heights used in the network. Were such a capability to be established across the country, a national spatial correction grid could likely be developed and used to adjust both individual site records and/or in conjunction with existing areal rainfall products (e.g. CEH-GEAR; Keller *et al.* 2015).

## CONCLUSION

This study presents, for the first time in the UK, a field trial of storage, TBRs and WRGs to investigate the impact of changes of raingauge siting within the UK operational network on wind-induced undercatch. These results presented here support the need to consider further the homogeneity of rainfall records in light of changes to gauge height within the UK, with the amount of undercatch almost double (on average) for the gauge installed at 1 m compared with 0.305 m. Investigations into the drivers of the observed undercatch using the event dataset suggest that the impact of gauge rim height is more evident at higher wind speeds and during low-intensity rainfall events but that the weakness of these relationships in the observed data prevented the development of a correction factor in this location.

The results of this study highlight the importance of understanding changes in raingauge undercatch as networks evolve. Where such changes are not communicated to data users and/or corrected for, they may complicate the detection of long-term changes in water balance calculation (e.g. Marsh & Dixon 2012) and the investigation of significant hydrological events (e.g. Barker *et al.* 2016). On the basis of this study, the authors aim to extend the field trials at Wallingford and use high-resolution rainfall and wind speed data to improve understanding and explore the generation of at-site correction factors. Improvements to the experimental set-up are also being considered, including options for measuring wind speed at the gauge rim height and dynamic calibration of the TRBs across a range of intensities (as recommended in CEN (2012)).

The results presented in this study are from a lowland UK site. Previous studies suggest that higher undercatch could be expected at more exposed upland sites and the knowledge of spatial variation in undercatch with varying topography is currently poorly understood, both in the UK and globally. As such, it is recommended that to prevent this introduction of inhomogeneity in time series, any future installation of replacement gauges are done at the UK standard height of 0.305 m or, to further improve the understanding of undercatch and develop adjustment methods for rainfall data, a network of International Standard reference pit gauges need to be constructed around the UK (and in other countries) with full metadata detailing their siting.

While the focus of this study has been on the inhomogeneity which may be introduced to the UK rainfall records by changing gauge rim height, the authors acknowledge that the UK practice of installing gauges at 0.305 m is different from that in many other countries. In locations where the standard installation of gauges is higher, it will be easier to maintain consistency with changing gauge designs. However, the magnitude of the undercatch observed in this study for gauges installed at 1 m is of relevance to all networks with rim heights of this level and above. Precipitation time series are often used to underpin a wide variety of hydrological science and operational water management decisions. For such applications, it is the amount of water reaching the ground surface which is often of interest and hence, unless properly understood and accounted for across space and time, undercatch of the magnitude of the 12.7% observed in this study and potentially even higher, represents a significant uncertainty in catchment hydrology and therefore the management of water resources and water-related hazards.

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