Accurate Rainfall Measurement: The Neglected Achilles Heel of Hydro-Meteorology

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Abstract

Rainfall measurement has an extensive historical precedent. Attempts have been made to standardise measurement procedures. This has never been successfully achieved. There are many sources of measurement error, some of which are compounded by poor rain gauge siting and a variation in gauge height. By far the worst cause of measurement inaccuracy is due to wind-induced undercatching. Some solutions have been proposed to tackle this problem but none have been fully implemented, and little has been done on the topic for several decades.

Rain gauge intercomparisons performed for different types of rain gauges situated at a standard height showed that the design shape of the gauge is significant, in terms of measured rainfall catch. The type of rainfall event was also shown to be significant, with events typical of west-coast UK uplands shown to be more susceptible to wind-effects than a large convective event on the UK's east coast. Different types of instruments were also demonstrated to have varying degrees of sensitivity to rainfall, further complicating the measurement process.

A number of key findings are presented which pertain to; the aerodynamics of the gauge itself, the type of rainfall event and wind conditions, the siting of the rain gauge, and why there is a pressing need for standardisation of rainfall measurement. Implications of the findings describe an inconvenient truth in hydro-meteorology which transcends a variety of applications of rainfall data, from real-time flood forecasting to Numerical Weather Prediction models.

Having discussed the problem and the importance of solving it, the experimental design of a multi-site field experiment is discussed, supplemented by the use of Computational Fluid Dynamics (CFD) simulations.

Introduction

The accurate measurement of precipitation is vital in hydrological network monitoring and in climate studies, agriculture and forecast applications. Wind induced undercatching in rain gauge networks is a longstanding issue which has not so far been decisively dealt with. All historical precipitation measurements are therefore systematically deficient. The extent of this undercatch is unknown and constantly varying, due to the complexity of the inter-relationship between a set of dependent variables. The only method of accurately measuring the correct rainfall catch is by using a WMO reference pit rain gauge.

Rainfall measured by a rain gauge at a height should be a true representation of what would have actually hit the ground if the gauge was not present. The trajectories of precipitation particles become distorted in a wind through the displacement and acceleration of wind flow over the top of the gauge as caused by the aerodynamic blockage by the gauge body (Goodison et. al, 1998). Assuming a correctly calibrated instrument, the extent of reduction (undercatching) due to the wind effect is a function of the wind speed at gauge orifice (and inside the gauge), precipitation type and particle falling velocities (drop size and distribution), rainfall intensity and the aerodynamic properties of a particular type of gauge. Furthermore, these variables are contingent upon the local climatology, so the wind-induced undercatching is therefore site and season dependent. Attempts have been made to carry out some correction based on existing data and empirical procedures, but the physical nature of this complex mathematical function has not yet been described in the literature.

Rainfall measurement errors: a definition of terms

Catching: Errors due to the atmospheric conditions at and around the collector (e.g. wind); as well as wetting, splashing and evaporation (Lanza et al., 2005).

Counting: The capacity of the instrument to correctly 'sense' the amount of water actually collected by the instrument (Lanza et al., 2005).

Throughout the 19th and 20th Centuries, work has been undertaken to document the 'catching' errors in rain gauges (summarised in Fig. 1). The uncertainties that exist specifically with regard to wind are noteworthy. The limiting factor for decisively dealing with the problem during the 20th Century was technology. Measurements were taken manually at a coarse resolution (monthly or daily) due to the limitations of achievable data resolution. This type of 'counting' error differs from the mechanical 'counting' errors such as those which TBRs are susceptible to. Therefore, whilst modern TBR rain gauge networks have increased the data resolution capacity, they are vulnerable to mechanical instrument-based 'counting' errors. Manual rain gauges can mask the highly dynamic constantly varying extent of wind-induced catching errors, due to coarse data resolution. Empirical work has been conducted regarding the wind field deformation around rain gauges. The last serious effort made to do this was by Strangeways (2004). Figure 2 (Strangeways, 2004) empirically describes the turbulent nature of the flow field around the gauge. Approaching the problem differently, Nespor and Sevruk (1999) developed a method to numerically simulate the three dimensional airflow around a precipitation gauge.

Approximate errors in precipitation measurement (Kurtyka, 1953.)

Source	*% error*
Evaporation	−1.0
Adhesion	−0.5
Colour	−0.5
Inclination	−0.5
Splash	+1.0
TOTAL	**−1.5**
Exposure (wind)	**−5.0 to −80.0**

Fig. 1. Highlights the extent of the uncertainty regarding the catching errors in rain gauges. This graphic assumes that there are no counting errors (Rodda, 2012).

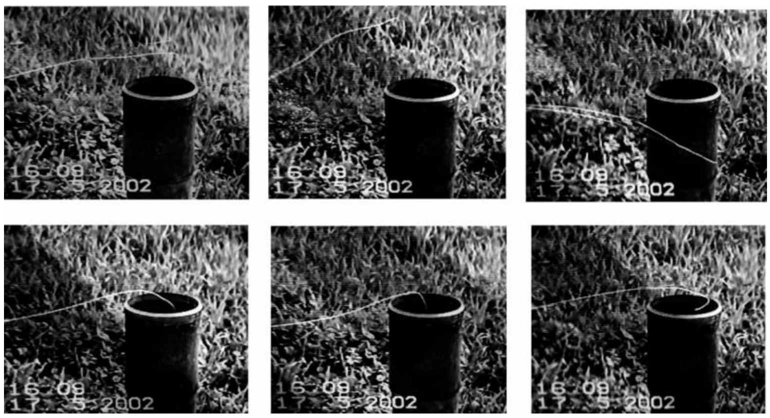

Fig. 2. An empirical description of the turbulent nature of the flow field surrounding a rain gauge (image courtesy of Strangeways). A piece of string was affixed to as stick upwind of the gauge and was captured as it moved, frame by frame.

Research question

There are a great number of different types of rainfall events, which vary hugely according to factors such as latitude, temperature, geography, atmospheric conditions etc. The context of this research originated from study of a particular type of rainfall event, extremely common in certain areas of the UK.

During work conducted by Wilkinson (2009) at Newcastle University it was noted that there are many low intensity light rain – or 'drizzle' – events in Cumbria, UK. These can last many hours and sometimes persist for days. Many parts of this county are also susceptible to higher wind speeds (daily average often exceeding 5 m/s in winter). However, it was also noted that on some days where it was visually possible to see rain, the rain gauges were not collecting any rainfall. Furthermore, it was discovered that the water balance for a number of different Cumbrian catchments were consistently showing significantly less precipitation (inputs) than discharge (outputs), which remained the case after other factors were taken into account.

It was considered whether the *a priori* argument of low intensity rainfall being highly affected by the wind, and the effect of rain shadowing, could cause significant rainfall underestimation. If this could be proven even at one location, there would be a serious case to investigate further the extent and implications of this inaccuracy throughout the UK.

Methodology

Investigating the problem in the Eden Catchment, Cumbria, UK.

The Eden catchment was selected due to its geographical location within Cumbria in the UK. In general, Cumbria is widely known to be highly susceptible to prevailing South Westerly winds. These winds tend to whip up moisture from the Atlantic and the Irish sea, delivering it as orographic rainfall throughout the undulating terrain of the county.

An instrument intercomparison was set up to study how gauge shape and operating principle affects rainfall catch. An exposed UK site in Cumbria, called Newton Rigg, is shown (Fig. 3).

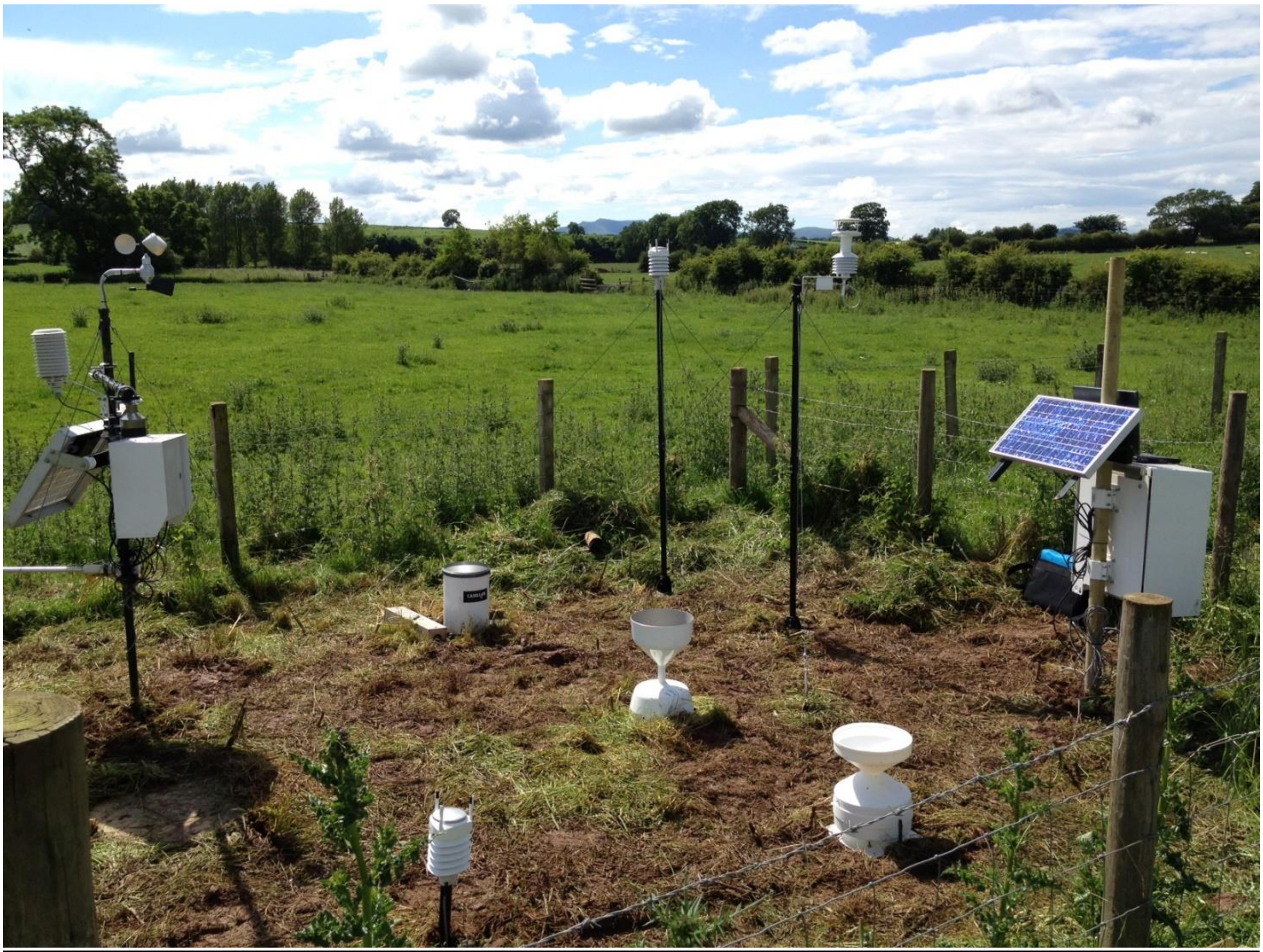

Fig. 3. Instrument intercomparison site at Newton Rigg, Cumbria, UK. This site includes tipping bucket rain gauges (TBRs) and acoustic disdrometers.

The instrument enclosure consists of three tipping bucket rain gauges (TBRs) mounted on the ground surface. Two of these gauges have an aerodynamic wind profile designed to minimise the effect of wind (Strangeways, 2004). One of the gauges was of a conventional cylindrical shape. There was no WMO reference rain gauge pit at this site.

Two multi-weather sensors (equipped with rainfall measurement) were installed; one measured wind and rain at gauge orifice height, and the other measured wind and rain at 2 metres. There was an additional multi-weather sensor installed at a height of 2 metres to ensure wind data integrity.

Preliminary results

Preliminary results show a significant variation in catch between different instruments (Fig. 4). Fig. 5 shows differences in average daily wind speeds measured at gauge orifice height compared to the standard UK measurement height of 2m.

Initial results show four different instruments measuring rainfall in the same geographical location, two tipping bucket rain gauges (TBRs) (one conventional straight sided and one aerodynamic), and two acoustic disdrometers (one mounted at 0.3m and one at 2m). During the 7 month comparison period the difference between the best and worst performing instrument was 117mm, equivalent to 31% of the maximum measured amount. When considering that even the best performing instrument is undercatching to an unknown extent, this poses some interesting research questions.

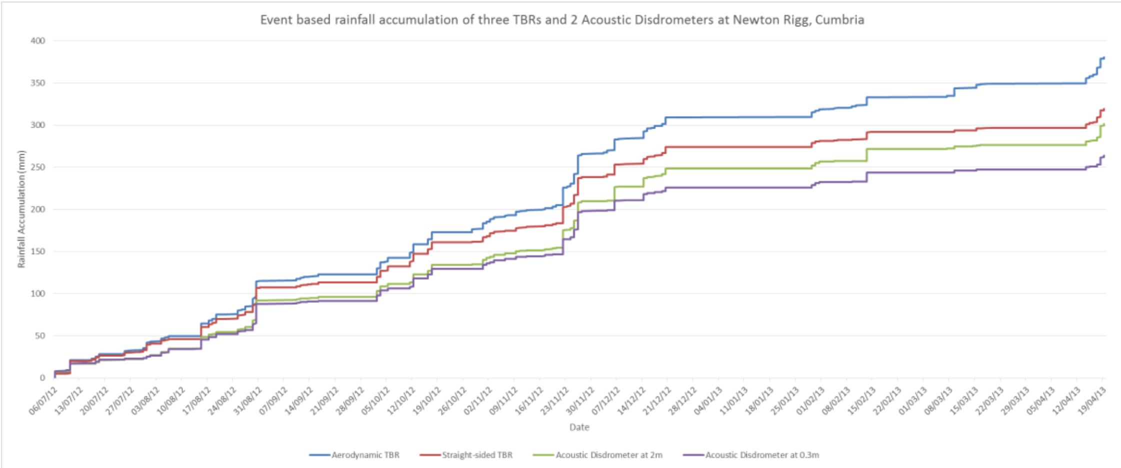

Fig. 4. Intercomparison between four instruments on rainy days over 7 months at Newton Rigg, Cumbria.

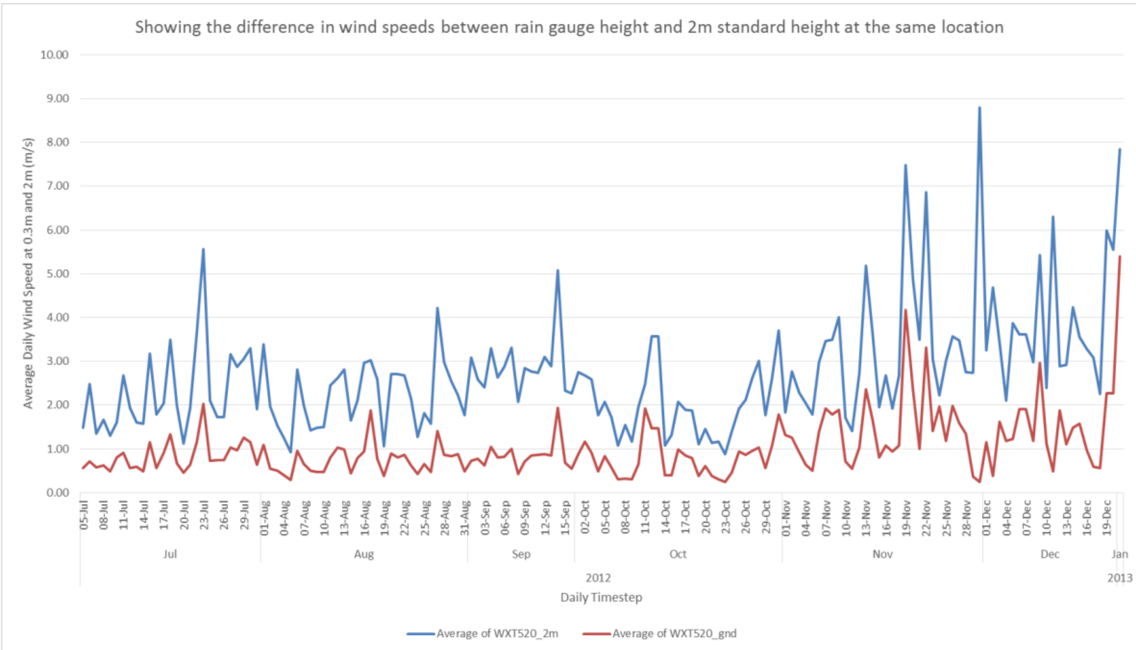

Fig. 5 Daily average wind speeds at gauge orifice level (in red) compared to 2 metres (in blue) (standard measurement UK measurements) at Newton Rigg over a period of 6 months.

In Fig.4 it is shown that the straight sided TBR measured 15% less rainfall over the time period than the aerodynamic TBR. The gauges were identically calibrated. Over a different time period at the same site this percentage was around 20% (graph not shown). This points towards a dynamic but systematic inaccuracy. Fig. 5 shows the variation in wind speeds which are likely to effect the extent of this error in any given rainfall scenario.

Further Work

A new collaborative project commenced in 2013 between Newcastle University and Environmental Measurements Limited (EML) (principal investigators), supported by, - Dundee University and the James Hutton Institute (JHI) (Aberdeen). Four densely instrumented field sites are currently being installed. These sites include WMO reference pits (equipped with TBRs and a weighing gauge), optical disdrometers and 3D wind sensors. They will measure data at a high resolution, from which site-specific catching-error correction procedures will be developed. The TBR intensity correction procedures developed by Lanza et al. (2005) in the WMO Laboratory Intercomparison of Rainfall Intensity gauges will be applied.

The four densely instrumented sites are representative of different weather patterns within the UK. Each site is equipped with a pit containing four rain gauges, two duplicates as statistical replicates and a total of three with different operating principles. This is to measure the reference value for rainfall accumulation and intensity. An identical setup is being installed above ground adjacent to the pit, allowing for direct comparison. This will form a fundamental basis for the correction. The most important variables to measure at a high resolution to form a correction are: drop size distribution (or precipitation type as a parameterised equivalent), rainfall intensity, wind speed at gauge orifice and gauge shape. The experimental design of the primary site at Nafferton Farm in North East England (currently being installed) can be seen in Fig. 6 below (units in mm). One other site is an expansion of the Newton Rigg site in North West England (Cumbria). The two remaining sites are located in South East Scotland and South West Scotland.

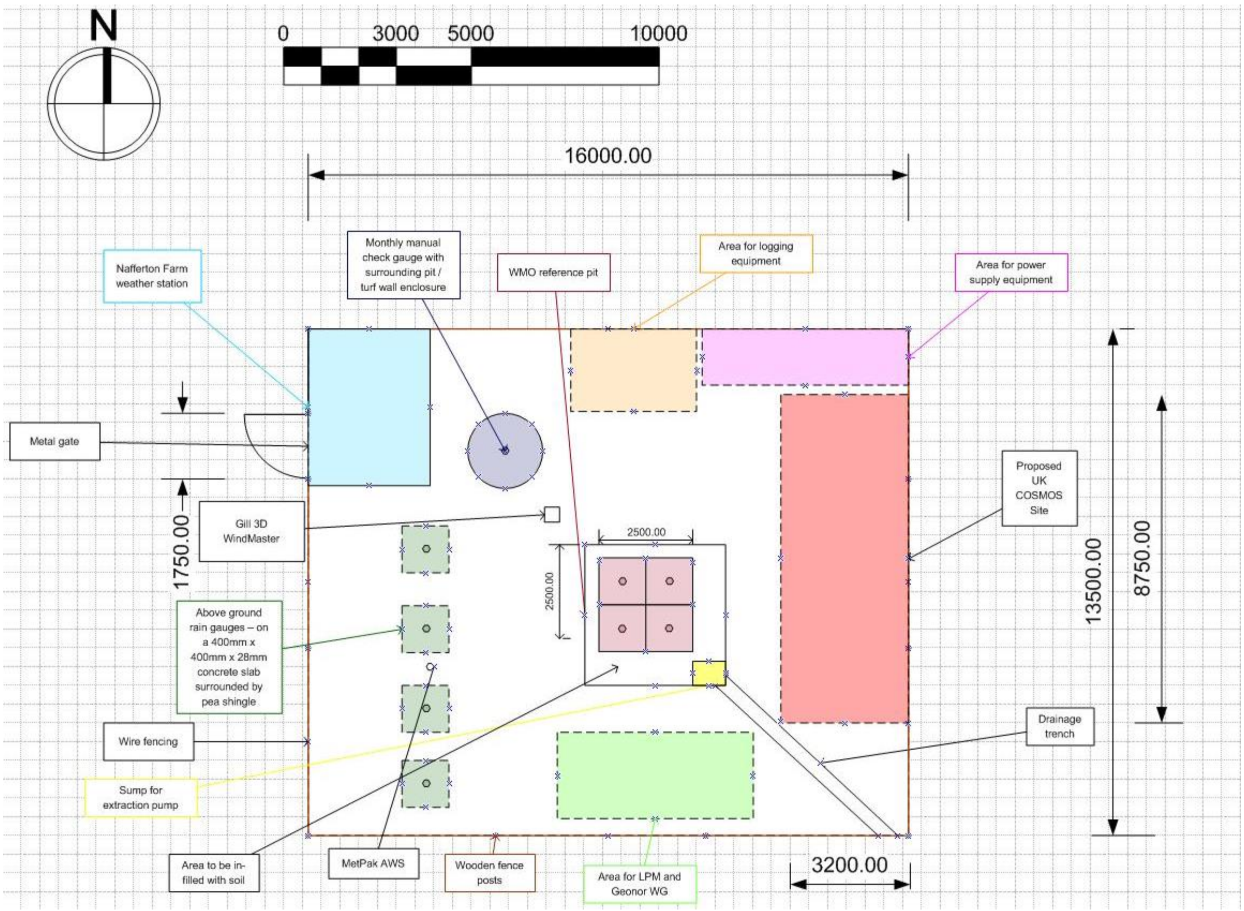

Fig. 6. Experimental design of the Nafferton Farm site (Tyne and Wear, UK) when fully furnished with all instrumentation

The scope of the project aims to solve the wind induced catching errors for the Environmental Measurements Ltd (EML) range of aerodynamic TBRs. A limitation is that it will not be able to provide a correction for other gauge shapes and measurement principles. A large scale WMO-led Field Intercomparison should be organised to achieve this.

Project deliverables

- Raise the profile and create a renewed awareness of the wind effect bias within the global hydro-meteorological community
- Develop a suite of correction algorithms to apply to existing aerodynamic rain gauges based on evidence collected at four experimental sites
- Develop a method to confidently upscale the wind bias correction methods to represent regional zones within the UK
- Produce a number of papers presenting and validating the case for using a real-time correction

The project will also develop a new rainfall measurement instrument through EML that will incorporate a real-time wind correction algorithm. This piece of equipment will be designed for applications where precise and accurate real-time self-correcting measurements are essential.

To describe the wind field flow patterns around the rain gauge, a combined ‘monitoring and modelling’ approach will be taken. Empirical procedures using tracers and high resolution video evidence from field experiments will be used to validate Computational Fluid Dynamic (CFD) simulations of the airflow/turbulence around EML aerodynamic rain gauges. An example of these CFD simulations for a weighing gauge is seen in Fig. 7.

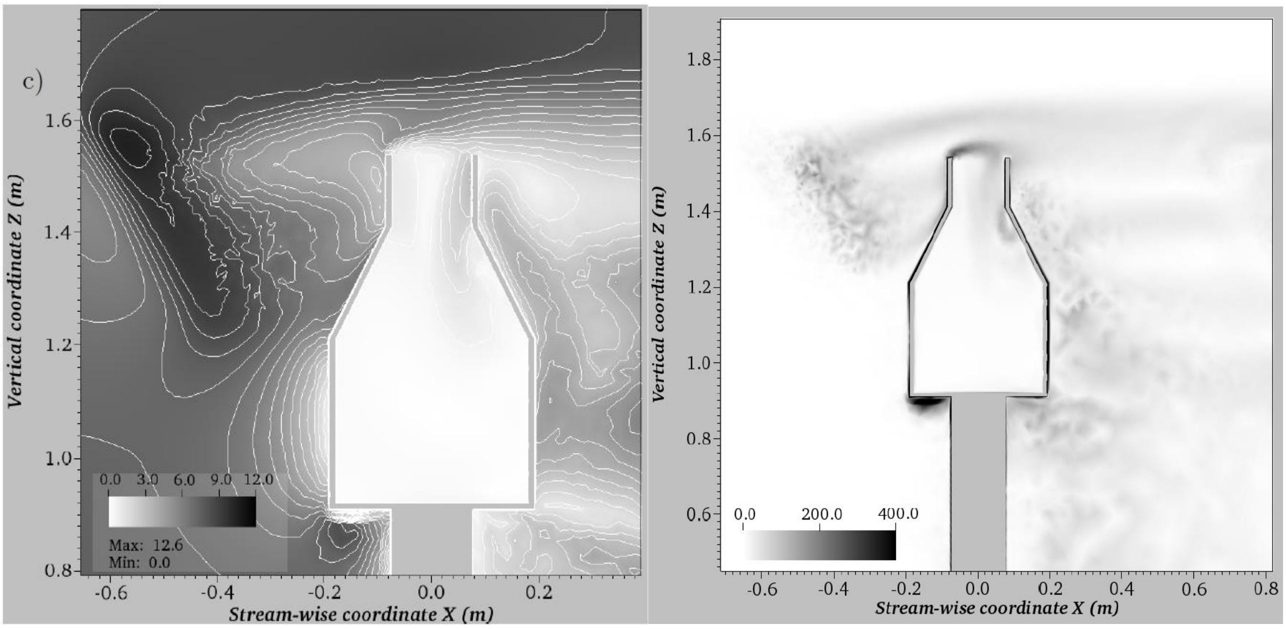

Fig. 7. Computational Fluid Dynamic (CFD) analysis showing the wind field deformation caused by a weighing rain gauge with wind shield, when a uniform wind speed of 8 m/s is applied (Colli, 2014).

Concluding remarks

Increasing the achievable temporal resolution of data by improving the measurement technique has introduced different sources of instrument bias (counting errors). Through the work of the WMO Rainfall Intensity Laboratory and Field Experiments (Lanza et al., 2005, Vuerich et al., 2009), it is now known that instrument accuracy in the laboratory can be achieved by using an appropriate correction algorithm. It is vital to use this new knowledge to address the long-standing problem of solving rain gauge catching errors in the field. With the emergence of newer technologies, there is great potential to solve this problem. However, with more equipment being brought to market, and with ‘new’ and ‘innovative’ technologies to measure the rain, it is becoming apparent that scientific rigour and academic discipline should be applied to ensure the integrity of the measurement process is not compromised.

There is undoubtedly a place for new technologies, and arguably the only way to solve the measurement problem is by pursuing these. However, without any correction for or, in many cases, any awareness of the errors introduced by wind, there is a grave risk of a breakdown in the understanding of hydro-meteorological sciences in a scientific era dominated by modelling which undervalues the principals of precise and accurate measurements.

It is difficult to overemphasise the extent by which a comprehensive and robust field intercomparison is needed, using the knowledge gained from the correction of instrument 'counting' errors in the Laboratory Intercomparison. One of the most important elements of this inherently vital and necessary piece of work will be the selection of sites. It will be of great importance to select some windy sites susceptible to orographic relief rainfall, such as many regions in the UK.

For such a fundamentally important subject, the study of how water moves and interacts throughout land and atmosphere, there remains a chink in its armour which has the potential to seriously cripple the intellectual integrity of the subject if it remains unchecked. In the context of a changing climate where rainfall patterns in the UK are due to change (Kendon et al, 2014), there remains a fundamental lack of understanding of the current rainfall measurement systems. It is scarcely believable that Jevons (1861) first commented upon the deficiency of rainfall in an elevated rain gauge in 1861, and, 150 years later the problem remains unresolved. Rainfall measurement could be the Achilles' heel of hydro-meteorology, unless something is done about it soon.

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