THE EXTENT AND IMPLICATIONS OF INACCURACIES CAUSED BY WIND-INDUCED UNDERCATCH ON RAIN GAUGES IN THE EDEN CATCHMENT

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Declaration

I hereby certify that this work is my own, except where otherwise acknowledged, and that it has not been submitted previously for a degree at this, or any other university

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Abstract

Empirical procedures based on WMO intercomparisons and numerical simulations have developed methodologies to correct for wind-induced undercatch. The degree of confidence in a particular correction model is a function of the availability, accuracy and temporal resolution of the input variables. The UK systematically underestimates the input to its water resources through a lack of adequate consideration of undercatch. Investigations at several spatiotemporal scales in the Eden catchment apply various correction models based on the resolution and availability of input data. Recorded rainfall measurements are found to be always deficient, with between 3-20% monthly undercatch at a rural lowland site and over 30% at an exposed upland site subject to high wind speeds. A very small but very significant relationship was found between undercatch and both rainfall intensity and wind speed. Correction models tend to vary seasonally. A suggestion is made to begin work on the development of a regional undercatch correction model for the Eden catchment, ideas are presented on how this can be achieved.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

The widespread flooding during the summer of 2007 across the British Isles constituted the country's largest peacetime emergency since World War II (CO, 2008). Sir Michael Pitt's review of these floods was the primary catalyst for major developments in operational hydrometeorology in the UK (Dale et al., 2012). In the context of a changing climate the importance of accurately measuring the precipitation events which cause such catastrophic flooding is rising to prominence in the UK. At the other end of the climatological spectrum widespread water shortages particularly in the south east of England are driving the need for more accurate estimation of the input to the UK's water resources.

The precise measurement of precipitation is also vital for climate studies, agriculture, forecast applications and hazards mitigation (Durkee, 2010), but its measurement is much more complicated to achieve than is generally appreciated (Strangeways, 2010).

With ground-based precipitation measurement there is a long standing issue of wind-induced undercatching which first rose to prominence as early as 1862 when the British scientist William Stanley Jevons produced a study "on the deficiency of rain in an elevated rain gauge". Over the subsequent centuries hydrological knowledge has developed considerably in a wide range of spectra. During the past 50 years the magnitude, detail and temporal resolution of precipitation observation records, particularly at global scales, has been systematically archived. However, the problem of accurately measuring precipitation appears to remain a challenge which has not so far been decisively dealt with, and many uncertainties in historical precipitation data have not yet been comprehensively quantified.

The driver of this project is the need to better understand the issue of undercatching of rain gauges, particularly for the significant inaccuracies caused by the effect of wind.

2. AIM AND OBJECTIVES

2.1. Aim

To investigate the extent and implications of inaccuracies caused by wind-induced undercatch on rain gauges in hydrological networks by assessing their accuracy and reliability. The implications on flooding, water resources and climate change studies will be discussed using a critical review of literature, with testing of new and conventional equipment in field studies and theoretical analysis.

2.2. Objectives

- Carry out a comprehensive literature review on the current levels of understanding regarding precipitation measurement and correction procedures
- Investigate the performance of new and conventional instrumentation through analysis of local-scale datasets and carry out appropriate statistical analysis to assess the significance of any findings
- Carry out a long-term analysis of historical archive data, assessing the accuracy of recorded precipitation measurements and explaining any climatic trends which are found

3. LITERATURE REVIEW

This chapter provides a critical review of the importance of accurate precipitation collection, and the instrumentation widely in use for its measurement. A detailed study of rainfall correction methods is also included.

3.1. Importance of precipitation collection

Precipitation measurements are important for many applications in meteorology, hydrology, agriculture and climate research (Sevruk, 2006). In hydrology, they are used to evaluate the areal precipitation and provide vital input data to flood zone planning and prediction models, and assessment of water resources.

3.1.1. Hydrological monitoring networks

Environmental monitoring provides the scientific basis for reducing uncertainty and informing policy and decisions in a complex and changing world. Hydrological monitoring networks are designed to assess the balance of a watershed and benefit greatly from integrated approaches to their design and management. With water scarcity and drought becoming a major problem particularly in the South East of England, there is a growing need for the UK to better monitor and understand the input to water resources. For hydrological studies, elevated can-type precipitation gauges are operated in networks consisting of several gauge sites selected according to the main characteristics of the area and precipitation fields of interest (Sevruk, 2006). The number and distribution of rain gauges needed for a particular area will depend on the natural variability of precipitation and upon the purpose for which the data are collected, since this will determine the detail and accuracy of measurements required (Robinson, 2006). Simple point measurements are converted to areal precipitation using various interpolation techniques such as kriging, thiessen polygons and inverse distance weighting. It is vital that errors are corrected prior to the use of the measurements in quantitative applications otherwise they risk being propagated to the applications using them (Michelson, 2004b). For example, a 10% error of rainfall input may result in a 15-30% error in runoff output in hydrologic simulations (Chang and Harrison, 2005), this is corroborated by Wilkinson (2009).

3.1.2. CHASM and the Eden catchment

Catchment response varies with scale, and in the UK four mesoscale catchments (10^2 – 10^3 km^2) were selected to be instrumented at the patch/hillslope, micro-catchment (1 km^2) and mini-catchment (10 km^2) scales as part of a major UK initiative (O'Connell et al., 2007).

The Eden was one of the four mesoscale catchments to be instrumented as part of the Catchment Hydrology And Sustainable Management (CHASM) initiative. It was funded by the Joint Infrastructure Fund (JIF) and instrumentation of the catchment was completed by 2004 (Wilkinson, 2009). The Eden DTC agricultural research project has effectively become the successor to CHASM, and the majority of the instrumentation installed in 2003 has now been removed after about 8 years of data collection (Bathurst, 2012). However, a central spine has been retained to provide context for the DTC study and which still keeps some continuity of the data record to date (Bathurst, 2012).

The high resolution study in this project uses instrumentation from Gais Gill, a high altitude upland site which has been retained as part of the old CHASM network and is maintained by Newcastle University. It also uses the data record of Newton Rigg, a lowland site which is part of the DTC project but is also monitored and maintained by Newcastle University. The other location studied was Great Dun Fell which used a longer data record obtained with special permission from the British Atmospheric Data Centre (BADC). Another site called Valley in Wales was also used to provide context and comparison which was also accessed through the BADC database.

3.2. Review of instrumentation

Methods for measuring precipitation should aim to obtain a sample which is representative of the true amount falling over the area which the measurement is intended to represent, whether on the synoptic scale, mesoscale or microscale (WMO, 2008). The purpose for which data are collected determines the detail and accuracy of measurements required, and therefore the type, quality and resolution of the instruments' capabilities. For example, much more detailed information is required for urban storm drainage design and for research purposes than for general water resource and supply projects (Robinson, 2006). Furthermore, the form of precipitation influences the network of gauges, snow for instance presents a unique set of problems and may be approached in different ways (Sevruk, 2006). A comprehensive review of the best approach to accurately measuring snow is detailed in Goodison et al. (1998). There are three basic types of precipitation gauges which differ according to the recording temporal resolution (Sevruk, 2006):

- Storage gauges – 1 month to 1 year
- Standard gauges – daily
- Recording gauges – high resolution (minutely to hourly)

Storage gauges are not considered in this study because higher resolution measurements are available.

3.2.1. Standard gauges

Strangeways (2006) defines the term ‘raingauge’ as a device that collects water in a funnel and measures it in situ. The amount of water collected may be measured by manually emptying a storage raingauge and noting the amount of accumulated water (Robinson, 2006). Kurtyka et al. (1953) referenced 1079 gauge designs and out of these Rodda and Dixon (2012) report there are over 80 different national standard manual gauges in use worldwide which measure daily precipitation. The Russian Tretyakov gauge, the Hellman gauge, the Canadian Nipher gauge and the UK Met Office Mark 2 appear to be among the most commonly used national standard manual collecting gauges (Goodison et al., 1998). However, these gauges have similar physical properties so only the UKMO MK 2 gauge will be briefly described.

UK Met Office Mark 2 rain gauge

Since the beginning of the 20th century the UK has retained the same standard gauge for precipitation measurement, the UKMO MK2 is the 3rd most widely used non-recording precipitation gauge (Sevruk and Klemm, 1989). It stores the collected water in a bottle below ground, holding the equivalent of 74 millimetres of rain, and is read daily using a graduated measuring cylinder (Strangeways, 2010). Field tests carried out in the 19th century compared around 50 gauges and resulted in what became the standard five-inch rain gauge with its rim one foot above the ground (Burt, 2010)

Figure 1: Five-inch standard UK Met Office gauge, with graduated measuring cylinder (Strangeways, 2010)

3.2.2. Automatic recording gauges

Sevruk (2006) states that float system-type recording gauges are most common, however Strangeways (2006) argues that tipping bucket raingauges (TBR) are most widely used which is in agreement with (Habib et al., 2010). When a pre-specified amount of rain has accumulated in the upper of two buckets which are balanced in unstable equilibrium, they become unstable and tip over, giving a contact-closure which is recorded by a data logger (Habib et al., 2010; Strangeways, 2010). There are several other lesser used types of automatic gauges such as weighing raingauges, capacitance gauges, optical gauges and drop-counting gauges (Strangeways, 2010). However it is worth noting that gauge improvements after the introduction of the TBR mainly focus on developing the aerodynamic shape to minimize the effects of wind, first explored by Jevons (1862). In addition, over the past 10-15 years significant improvements have been made in the development of user accessibility, with the introduction of telemetry. Figure 2 shows the three TBRs which are used in the study. The ARG 100 and the SBS have a funnel shaped collecting vessel which is designed to minimize the effects of wind. The Casella Cel is of conventional cylindrical shape similar to standard gauges such as the UK MO Mk2. Also shown in c) is the tipping bucket mechanism which is contained within the base of all three gauges.

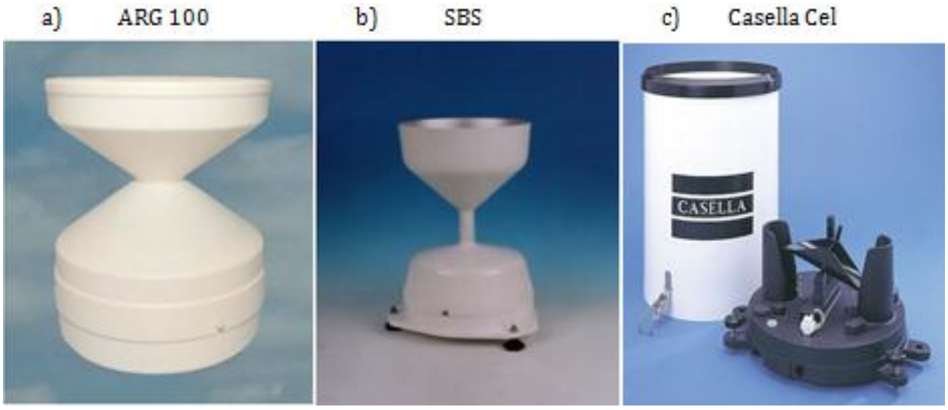


Figure 2: The three TBRs used in the study (EML, 2012; Casella, 2011)

3.2.3. Automatic weather stations and weather transmitters

Automatic weather stations provide a preconfigured robust solution to providing quality controlled data in meteorological applications. AWS are equipped with the capability of transmitting data for a wide range of meteorological variables through telemetry. They allow for the integration of many variables within one monitoring station with low marginal cost, both in investment and operation (Snorrason and Puupponen, 2009). In the Eden catchment, due to a lack of solar energy the panels sometimes do not produce enough power to recharge the battery which runs the AWS. In addition, telemetry has proved temperamental so in most cases systematic downloads occur which require a person to visit each site, usually around once every 3 months. An AWS is installed at both Gais Gill and Newton Rigg, each is equipped with a thermometer, anemometer, wind vane, and attached is at least one precipitation measuring device.

Weather transmitters constitute a new generation of meteorological monitoring. They are small and compact devices capable of measuring all the atmospheric variables that an AWS monitors. There are different types of weather transmitters but this review covers the two types which are in use at the sites involved in this study: the MetPak II weather station and the Vaisala WXT520.

Both types of weather station are capable of measuring wind speed and direction, air temperature, relative humidity and barometric pressure. However, the WXT520 is particularly interesting because it has the capability of measuring precipitation. It is a “non-catching” type instrument which uses a sensor known as an acoustic/impact disdrometer to detect the impact of individual rain drops, with the signal from each drop being converted directly to accumulated rainfall (Vaisala, 2012). It is also capable of measuring rainfall intensity, duration and drop-size distribution in real time, which are becoming increasingly important variables in the science (Lanza and Stagi, 2009). “Significant biases” have been reported in the measurement of rainfall intensity by these acoustic disdrometers (Lanza and Vuerich, 2012). This needs to be addressed before they are considered a reliable substitute to catching-type rain gauges.

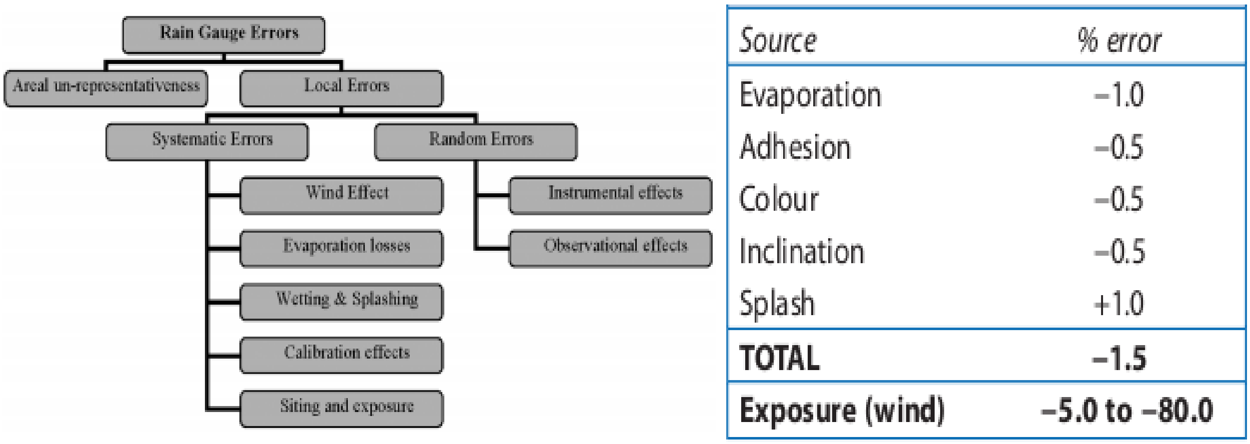
3.2.4. Remote sensing and radar

Remote sensing of precipitation is classified into two categories, passive and active. There are two types of passive remote sensing, one using visible and infrared techniques and the other using microwave techniques. Active remote sensing uses radar (Stephens and Kummerow, 2007). The main problem with remote sensing techniques is establishing a correlation between satellite data and ground truth data. Habib et al. (2010), Strangeways (2010) and Rodda and Dixon (2012) state that despite the advances in remote sensing the most precise measurements of climate will continue to be made in situ at the surface with instruments in direct contact with what they are measuring.

3.3. Undercatch of rain gauges

Measuring precipitation without introducing systematic errors or biases is difficult (Nespor et al., 1994; Sevruk, 2006). In the case of a common precipitation gauge, diameter of orifice, shape, material, colour, inclination, splash-in and-out, the means of storing catch and the method of measuring it, together with other design and installation variables can all contribute to a misrepresentation of the “true” precipitation catch (Goodison et al., 1998; Rodda and Dixon, 2012). Moreover, the physical characteristics of the prevailing weather and the gauge site can also influence catch (Sevruk, 2006).

Figure 3 shows the classification of rain gauge measurements and their resultant contribution of each component to rainfall error. The error estimations were made by comparing standard gauges against a reference gauge, which will later be explained in greater detail.



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**

Figure 3: Habib et al. (2010) flow chart of rain gauge errors (left) and quantification of approximate errors according to Kurtyka et al. (1953), reproduced in Rodda and Dixon (2012)

The comprehensive Kurtyka et al. (1953) study was conducted nearly 60 years ago but the conclusions still remain accurate (Rodda and Dixon, 2012). Most of the error sources from Figure 3 contribute to less than 1 % error. The uncertainty of error due to exposure to wind can be clearly seen, and this is an extremely important factor in explaining undercatch.

3.3.1. Wind-induced loss

The phenomenon of wind-induced error of precipitation measurement has attracted the attention of many scientists in the last two centuries (Goodison et al., 1998). It is a complex physical matter that was first highlighted by Jevons (1862) when he stated that "wind must move with increased velocity in passing over an obstacle". 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 of the gauge body (Goodison et al., 1998). The extent of reduction depends on the falling velocities of particles, wind speed and the aerodynamic properties of a particular type of gauge (Goodison et al., 1998). The adverse effect of the wind is that some of the lighter precipitation particles are borne away before reaching the gauge and are lost from the measurement (Sevruk, 2006). It should also be noted that errors for snow measurement are much greater than those for rain (Rodda and Dixon, 2012).

The process of wind-induced error is described by a set of differential equations of fluid dynamics and is still not fully understood (Goodison et al., 1998). However, wind tunnel experiments (Nespor et al., 1994) and numerical simulations (Nespor and Sevruk, 1999) have been carried out which have significantly developed knowledge of wind induced error for three operational types of rain gauge between a specific range of wind speeds (1 to 12m/s). The results show an increase of the error with a decreasing rainfall rate, and increasing wind speed and fraction of smaller drops (Nespor and Sevruk, 1999). When the results are calibrated with field intercomparisons they show relatively good agreement, however more work still needs to be done on this topic to attain better understanding. In a wind tunnel numerical simulation experiment Nespor and Sevruk (1999) demonstrated that when wind speed at gauge orifice was set to only 3 m/s, wind velocities above the orifice are approximately 35% higher than the free-stream velocity, this is illustrated in Figure 4.

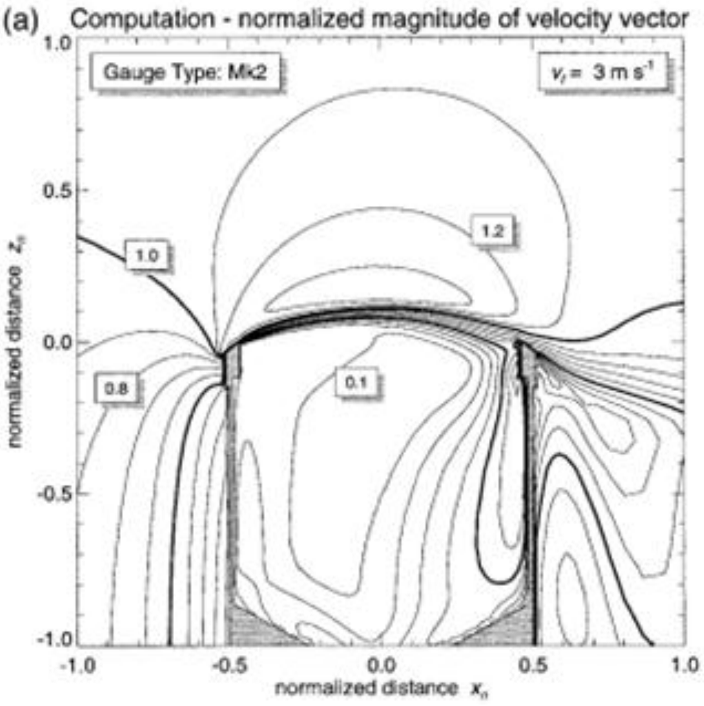


Figure 4: Numerical simulation of the wind field deformation caused by the gauge (Nespor and Sevruk, 1999)

Wind induced loss is smaller for large intensities (i.e. heavy raindrops), small installation heights (smaller wind speeds), gauges with windshields and those which are placed at protected sites (Sevruk, 2006). Kurtyka et al. (1953) state that wind induced loss can be as much as 80%, however it is generally considered that on average the loss for rainfall amounts to 2 – 10% for wind speeds of more than 4m/s, and is much higher for snowfall (Goodison et al., 1998). It is clear that the understanding of this topic is not complete, particularly low intensity precipitation measurements recorded at high wind speeds.

Chang and Harrison (2005) report another way in which wind affects rainfall measurements. They argue that rain gauges are designed to measure rainfall in vertical trajectories and that during storm events rainfall generally does not fall vertically because air is not calm. As a result, the raindrops fall into the gauge at inclined angles causing the effective catch-diameter of the gauge orifice to be reduced (Chang and Harrison, 2005).

3.4. Implications of systematic errors

Systematic errors frequently result in recorded measurements not being representative of “true” precipitation, which show a significant amount of variation between gauges of different construction installed at different heights (Sevruk, 2006). With around 50 national standard precipitation gauges and yet more TBRs worldwide, the global and local precipitation data sets are often not compatible (Sevruk and Zahlavova, 1994). To eliminate these systematic spatial inhomogeneities of precipitation time series, the performance of gauges has to be checked and the precipitation measurements corrected (Sevruk, 2006). Moreover, replacing a long serving gauge with a modern TBR or repositioning the new gauge can also cause inhomogeneities (Peterson et al., 1998). For example, at one of the gauge sites used in this study, Great Dun Fell, the standard manual gauge was replaced in the year 2000 with a recording gauge, but was moved 100 metres to the East. Such occurrences, along with many other precipitation measurement correction factors, are not afforded adequate appreciation in many hydrologic applications, with studies of suspicious quality still being published (Sevruk et al., 2009).

The effect of gauge site exposure on the quality of precipitation measurements is usually assessed using four classes of exposure; exposed, mostly exposed, mostly protected, and protected (Sevruk, 2006). According to De Smedt et al. (2003) this is based on analysis of metadata stored in archives of meteorological services. Unless precipitation measurements are corrected, the first two classes should not be used for hydrological studies due to considerable wind-induced loss (Sevruk, 2006).

From a national perspective, Rodda and Smith (1986) showed that volumes of rain are systematically underestimated at sites across the UK by between 5 and 20%, with underestimates being more serious at sites in the wetter parts of the country (Rodda and Dixon, 2012). Moreover in some of the UK's wetter catchments, including the Eden, the estimated percentage undercatch by standard rain gauges is approximately equal to the annual average evaporative loss (Hannaford and Marsh, 2008).

It is important to consider some of the broader implications of underestimating rainfall in the UK. In southeast England, the paucity of the mean residual rainfall coupled with the high density of population make the available water per head only slightly larger than demand (Rodda and Dixon, 2012). The most prominent area of concern relates to rainfall measurements in the context of climate change and its detection. Changes in spatial and temporal patterns of rainfall have been reported globally in IPCC (2007), and nationally for the UK by Osborn and Hulme (2002). For example, Fowler and Kilsby (2003) report that the magnitude of extreme rainfall has increased two-fold over parts of the UK since the 1960s. There are more than 80 types of national gauges around the world with individually unique errors, and no internationally agreed standard gauge. At present it is extremely challenging to detect, with confidence, differences in rainfall and attribute them to changes in climate (Rodda and Dixon, 2012). For example altered wind strengths and drop-size distributions may be occurring which might account for contrasts in catches, but this could equally be a manifestation of climate change (Rodda and Dixon, 2012).

3.5. “True” precipitation: a reference standard

There are two methods which could solve the significant problem of undercatch in hydrological studies. Development of instrumentation capable of accurately measuring true precipitation is the most obvious method, such as the deployment of a gauge in a pit or the use of wind shields. However, this is limited by financial and physical constraints (Goodison et al., 1998). In most cases, simple measuring instruments and uncomplicated arrangements are favoured. The resultant systematic errors are caused when the physical characteristics of the instruments interfere with other variables involved in the measuring process, and are responsible for the gap between “true” and measured precipitation (Goodison et al., 1998).

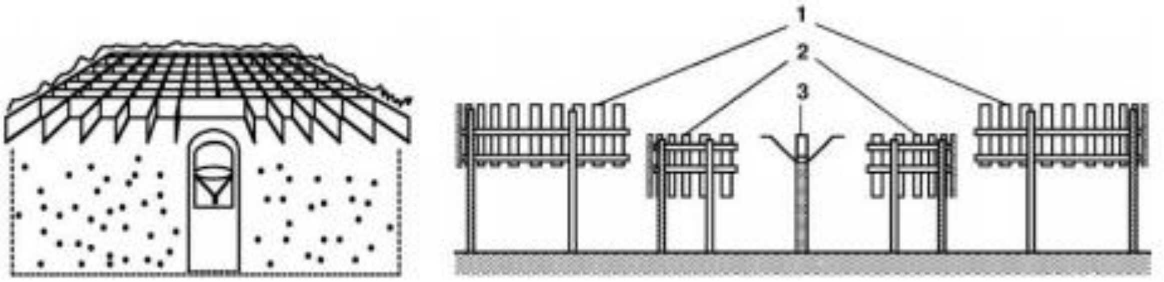
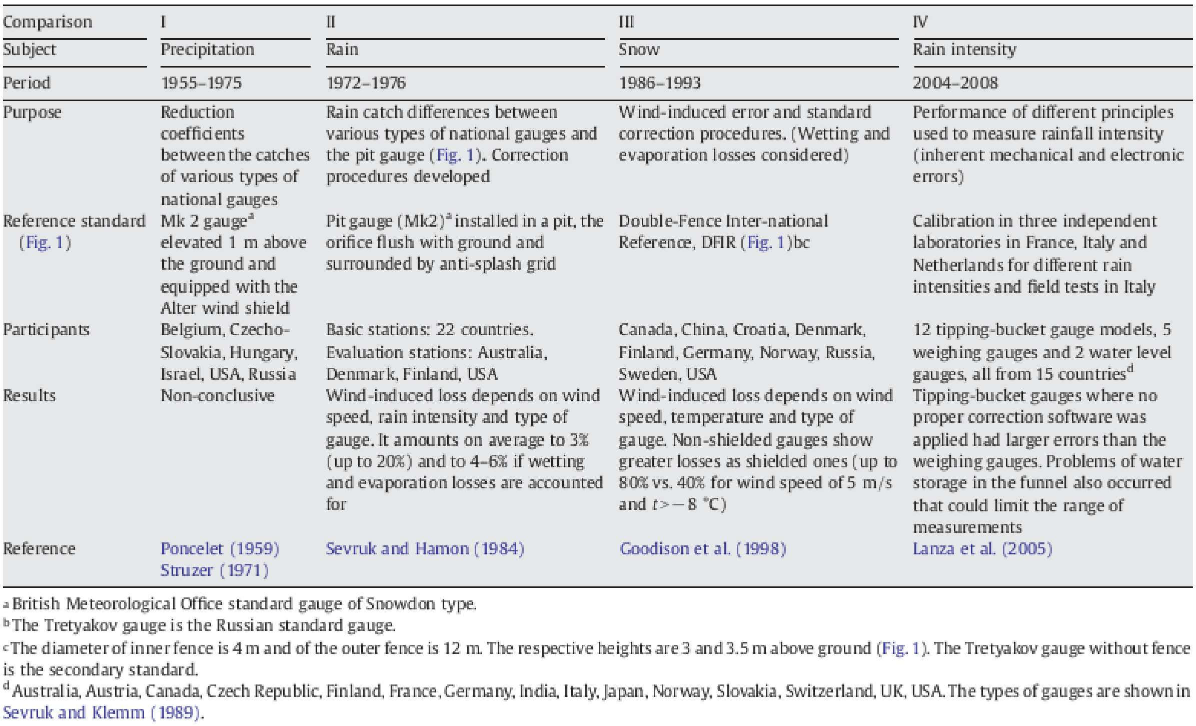


Figure 5: Reference standard gauges for rain (left) and snow (right) (Sevruk et al., 2009)

To eliminate the effects of systematic error, particularly wind-induced loss, the WMO established reference standards (Figure 5) and organised to-date four international intercomparison studies of precipitation gauge measurements to derive correction techniques (Sevruk et al., 2009). Table 1 provides a synopsis of these international precipitation measurement intercomparisons.

Table 1: WMO international precipitation measurement intercomparisons (Sevruk et al., 2009)



Comparison	I	II	III	IV
Subject	Precipitation	Rain	Snow	Rain intensity
Period	1955–1975	1972–1976	1986–1993	2004–2008
Purpose	Reduction coefficients between the catches of various types of national gauges	Rain catch differences between various types of national gauges and the pit gauge (Fig. 1). Correction procedures developed	Wind-induced error and standard correction procedures. (Wetting and evaporation losses considered)	Performance of different principles used to measure rainfall intensity (inherent mechanical and electronic errors)
Reference standard (Fig. 1)	Mk 2 gauge[a] elevated 1 m above the ground and equipped with the Alter wind shield	Pit gauge (Mk2)[a] installed in a pit, the orifice flush with ground and surrounded by anti-splash grid	Double-Fence Inter-national Reference, DFIR (Fig. 1)bc	Calibration in three independent laboratories in France, Italy and Netherlands for different rain intensities and field tests in Italy
Participants	Belgium, Czecho-Slovakia, Hungary, Israel, USA, Russia	Basic stations: 22 countries. Evaluation stations: Australia, Denmark, Finland, USA	Canada, China, Croatia, Denmark, Finland, Germany, Norway, Russia, Sweden, USA	12 tipping-bucket gauge models, 5 weighing gauges and 2 water level gauges, all from 15 countries[d]
Results	Non-conclusive	Wind-induced loss depends on wind speed, rain intensity and type of gauge. It amounts on average to 3% (up to 20%) and to 4–6% if wetting and evaporation losses are accounted for	Wind-induced loss depends on wind speed, temperature and type of gauge. Non-shielded gauges show greater losses as shielded ones (up to 80% vs. 40% for wind speed of 5 m/s and $t > -8$ °C)	Tipping-bucket gauges where no proper correction software was applied had larger errors than the weighing gauges. Problems of water storage in the funnel also occurred that could limit the range of measurements
Reference	Poncelet (1959) Struzer (1971)	Sevruk and Hamon (1984)	Goodison et al. (1998)	Lanza et al. (2005)

[a] British Meteorological Office standard gauge of Snowdon type.

[b] The Tretyakov gauge is the Russian standard gauge.

[c] The diameter of inner fence is 4 m and of the outer fence is 12 m. The respective heights are 3 and 3.5 m above ground (Fig. 1). The Tretyakov gauge without fence is the secondary standard.

[d] Australia, Austria, Canada, Czech Republic, Finland, France, Germany, India, Italy, Japan, Norway, Slovakia, Switzerland, UK, USA. The types of gauges are shown in Sevruk and Klemm (1989).

The reference standard for liquid precipitation involved the use of a standard gauge deployed in a pit surrounded by anti-splash protection, the gauge's rim flush with the ground level (Sevruk and Hamon, 1984). Pit gauges are hardly affected by wind, and if corrected for wetting and evaporation losses they give reliable results (Sevruk et al., 2009).

Establishing a reference standard for global liquid precipitation measurements was the first step to developing a method to accurately account for undercatch. However, there are a lot of other variables that need to be measured and calibrated before it is possible to correct a historical precipitation record.

3.6. Correction for systematic errors

There have been numerous local and regional scale and some global scale studies for different gauge types conducted to investigate and quantify the effect of wind speed on precipitation measurement. Larson and Peck (1974) reported that the undercatch percentages for an unshielded gauge increases at 2.24% for every m/s of wind. This agrees with Guo et al. (2001) who stated that undercatch ranges from 10 to 15% for wind speeds under 6.71 m/s and can increase to 56% for 22.36 m/s wind speeds. Figure 6 shows a number of gauge catch ratios measured against wind speed for four studies undertaken at different locations between 1965 and 1972. Even using these basic relatively linear correction factors would provide a significant improvement to historical records because wind-induced losses are not currently considered in published precipitation data and need to be corrected solely by the data users (Sevruk, 1996). However, as a result of the WMO's second intercomparison, correction procedures were significantly improved. Correction models developed were based mainly on field intercomparison measurements where the pit gauge is used as a reference for liquid precipitation (Sevruk, 1996).

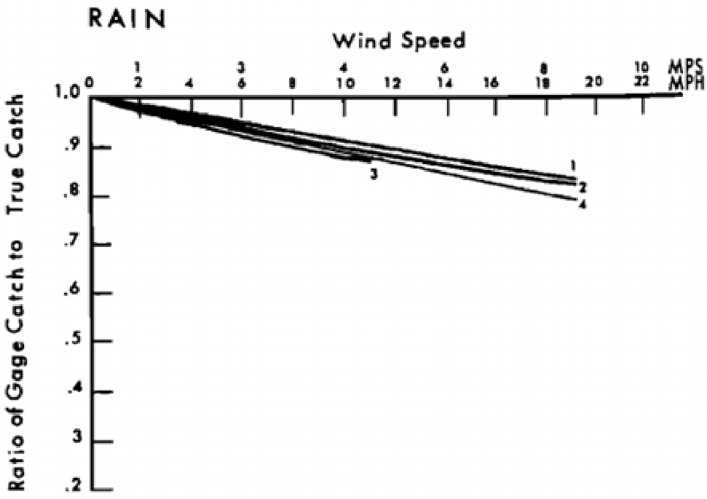


Figure 6: Gauge catch ratios versus wind speed where lines 1-4 represent different studies undertaken between 1965 and 1972 (Larson and Peck, 1974)

From the WMO rain intercomparison (1972-1976) numerous correction procedures have been developed for different types of precipitation gauge and various time intervals according to the availability of necessary input data (Sevruk and Hamon, 1984). A similar intercomparison study was initiated in 1986 leading to various extensions and improvements to the existing correction factors, procedures were developed to correct for snow (Goodison et al., 1998). The latest WMO intercomparison was based on improving the accuracy of high resolution measurements of rainfall intensity which is becoming an increasingly important parameter for correction models and is also of particular interest when analysing extreme events. The results of the laboratory stage of this project are reported in Lanza and Stagi (2009) and the field intercomparison is presented in Lanza and Vuerich (2009b).

Within the framework of the WMO studies different variations of the original correction procedure have been developed by a range of authors to suit a variety of gauge, weather condition, location and available input data (Allerup and Madsen, 1980; Goodison et al., 1998; Michelson, 2004a; Molini et al., 2005; Sevruk and Hamon, 1984). Sevruk (2006) states that these corrections are based either on empirical field methods using the WMO reference standard, or on numerical simulation as described by Nespor and Sevruk (1999).

According to Sevruk (2006) precipitation corrections are readily applied in many parts of Europe and the former USSR, however they are not in the UK. Input data include wind speed, precipitation intensity and weather situation (different drop-size distributions exist for different types of rain with the same intensity), temperature, rain/snow amounts, frequency of events, and so on (Sevruk, 2006).

Sevruk et al. (2009) under the auspices of the WMO claim that the most advanced corrections procedure for wind-induced losses is described in Sevruk (2006). This method is used for Great Dun Fell and is presented in Chapter 4. However, as the wind induced error strongly depends on the site surrounding, the prevailing wind speeds and the specific gauge form, it is difficult to recommend a specific method for universal use (Wagner, 2010).

To sum up, the need for the calibration and application of the correction of point precipitation measurements to increase their reliability is underlined in Sevruk et al. (2009). Numerous studies are still commissioned and presented which neglect the most recent WMO intercomparison results, producing poor results. In these cases relevant literature is not mentioned or ill-considered and the WMO recommendations are not followed, with precipitation measurements and insufficient analysis being presented as "challenges in obtaining reliable measurements of point rainfall" (Sevruk et al., 2009).

3.6.1. Recent advances of temporal resolution

The WMO advocate the application of intercomparison results for manufacturers to develop their gauges to become equipped with built in wind correction factors (Sevruk et al., 2009). However, more recent WMO intercomparison studies carried out between 2004-2009 focus on the performance of rainfall intensity instruments in high rainfall intensity conditions. Heavy rainfall is generally the origin of flash floods (Lanza and Vuerich, 2009a). In view of the high variability of rainfall intensity and evidence of a worldwide increase in both the frequency and intensity of heavy rainfall (Ekstrom et al., 2005; Fowler and Kilsby, 2003), measurements at a 1-minute time scale are crucial to enable proper measures to be taken to mitigate the impact of such events to save lives, property and infrastructures (Lanza and Vuerich, 2009a). As the return periods of heavy rain events are large, such as the deluge in

Newcastle-Upon-Tyne on 28 June 2012, long term records of rainfall intensity data are needed to estimate the probability of occurrence of heavy rainfall at a given location and time (Lanza and Vuerich, 2009a). Such measurements would also be used for better design of structures in terms of building and construction works, and infrastructure in terms of drainage, to mitigate severe weather impact (Lanza and Vuerich, 2009a).

More research needs to be conducted on this subject in the hope that a universal correction procedure can be developed that is sufficiently robust and dynamic to cater for the wide number of issues caused by the variety of different, rainfall intensities, drop-size distributions and wind field distortions which point precipitation measurements worldwide are subject to. However, to eliminate the wind field deformation completely for liquid precipitation, there appears to be no better method than using the WMO reference pit gauge.

4. METHODOLOGY

The importance of accurately measuring precipitation data has been previously discussed. The study aims to quantify the extent of undercatching and show how it varies, due to wind, in space and time. This section details the spatiotemporal approach used in an investigation of the accuracy of precipitation data. Two sub-sections included marking different scales of data resolution. The first explains the method for data collected at sites which are operated by Newcastle University and record high resolution rainfall measurements. The second describes the methods used to obtain and analyse datasets which operate at the daily measurement timescale. Data collection is discussed in the past tense in favour of clarity, however in most cases it is currently on-going with future studies in mind. Any present tense used denotes those methods which are generic in nature and commonly used.

4.1. Collection and analysis of high resolution data

Data is collected from the rural upland site of Gais Gill and from the rural lowland area at Newton Rigg. Statistical treatment of data provides the context for an assessment of confidence in results.

4.1.1. Gais Gill

Gais Gill is situated in the southwest of the Eden, which is a catchment located in the northwest of England. It is bordered to the west by the Lake District and to the east by the Pennine Hills. The measurement site itself is located in a rural upland part of the catchment, at the top of a small hill. The enclosure houses an automatic weather station (AWS) equipped with the capability of measuring a range of atmospheric and meteorological variables, and is set up to record these at 15 minute intervals. Attached to the AWS and also recording readings at 15 minute intervals are two different precipitation measuring devices. One of these is the ARG100 aerodynamic tipping bucket rain gauge (TBR) which is widely used in hydrological monitoring networks. The Vaisala WXT520 weather transmitter is the other device which is equipped with an “acoustic” (or “impact”) disdrometer, a new and innovative technique for measuring rainfall.

This station is equipped with telemetry which enables the user to log onto a satellite server and download data remotely. However, the system has proven to be temperamental in such a remote location so regular visits to the site are made by Newcastle University staff to download data. The information is collected in text file format and is transported into Excel for analysis. An initial dataset was available for the winter of 2010/2011 and it was hoped that more would become available. However, it became apparent that it would not be possible to obtain consistently reliable time series beyond the winter of 2010/2011. This was due to a failure of the battery power source, which was finally replaced in June 2012.

A summary of the data available for Gais Gill is provided in Figure 7 which shows a count of the number of readings made per day for both the TBR and the WXT520. The maximum number of readings made per day with 15 minute intervals is ninety six. This chart shows that the record is relatively complete with the exception of between the 6th and 24th of January 2011.

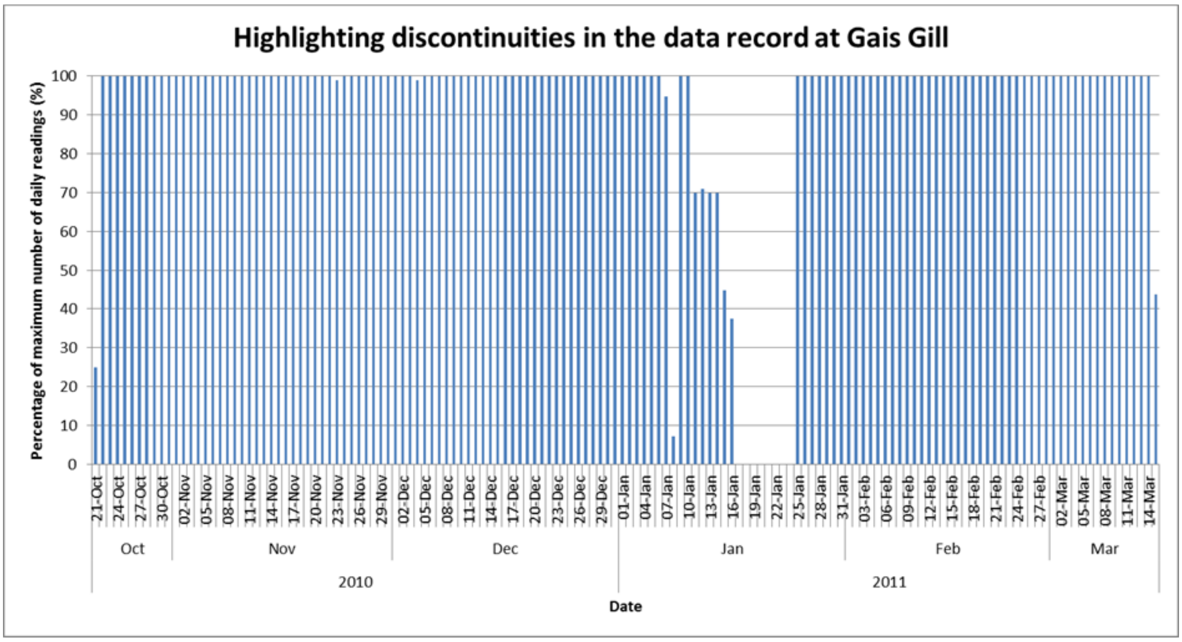


Figure 7: Chart highlighting discontinuities in the data record at Gais Gill

Both the TBR and WXT520 were connected to the AWS which meant that any failure in the power supply or general operating capacity of the AWS resulted in discontinuities which were uniform to both. For the purposes of a raingauge intercomparison it is only necessary to filter data if there is a mismatch in the number of readings per instrument. Both instruments recorded a total of 12, 798 readings which is further proof that no data needed to be filtered from this record. Therefore, it may be surmised that the raw data received from Gais Gill was in relatively good shape and did not require much adjustment. Having completed the data collection and checked the quality of the record, the process of analysis was commenced. Some simple measures were taken to graphically view and compare the total cumulative rainfall for both instruments over the period of observation. This was in order to gain a basic appreciation of how the two instruments performed in comparison to each other. Due to the issue of undercatch the wind speed at the gauge orifice height is also recorded and displayed.

To test if there was a significant difference between the cumulative amounts collected by each gauge a paired "t" test was used. To carry out this test it is necessary to calculate the difference between the two observations of each pair, making sure to distinguish between positive and negative differences. The mean difference can then be calculated followed by the standard deviation of the differences. This is used to calculate the standard error of the mean differences. By calculating the t-statistic it is then possible the compare the value against the t distribution in order to find the "p-value", which provides a measure of statistical significance.

The issue of undercatching precipitation gauges requires adjustment on the basis of a correction, as discussed in the literature review. Correction procedures require a number of different variables and are highly dependent on multiple factors such as the type of gauge and availability of input data. However, they generally assume the same basic equation to which other variables are derived or added. This is shown in Equation 1 where 'Pk' is the adjusted precipitation value, 'k' is the adjustment factor for the effects of wind field deformation and 'Pg' is the measured amount of precipitation.

Equation 1: General basis for wind-induced correction procedures

$$Pk = k \times Pg$$

An extensive study of correction procedures was carried out and it was established that there was no categorical agreement as to the best method to apply for all data records. Based on thorough investigation of relevant literature it was decided that the most suitable correction procedure to use given the available resolution of data and the type of raingauge was the Michelson (2004) “Dynamic Correction Model” (DCM). Reasons for the selection of this procedure are now discussed, along with the limitations of this approach.

Although uncertainties remain in the treatment of measurements from some gauge types, systematic correction using this DCM should lead to more accurate measurements for use in hydrometeorological applications (Michelson, 2004b). The ARG 100 deployed at Gais Gill is aerodynamically designed with a funnel shape to reduce the distortion of the wind field at the gauge orifice. The study conducted by Michelson (2004b) uses the Swedish SMHI gauge which is of conventional cylindrical design. However, the important point is that in this study the SMHI gauge is equipped with a Nipher wind shield, as shown in Figure 8. The effect of this wind shield on the amount of distortion caused by the physical presence of the gauge is also shown in Figure 8, with the wind speed velocity magnitudes referenced by colour and measured in metres per second. This modification changes its aerodynamic properties to become more similar to those of the ARG 100 TBR. It is by no means a direct representation but it is the most similar gauge-type that could be found in the literature.

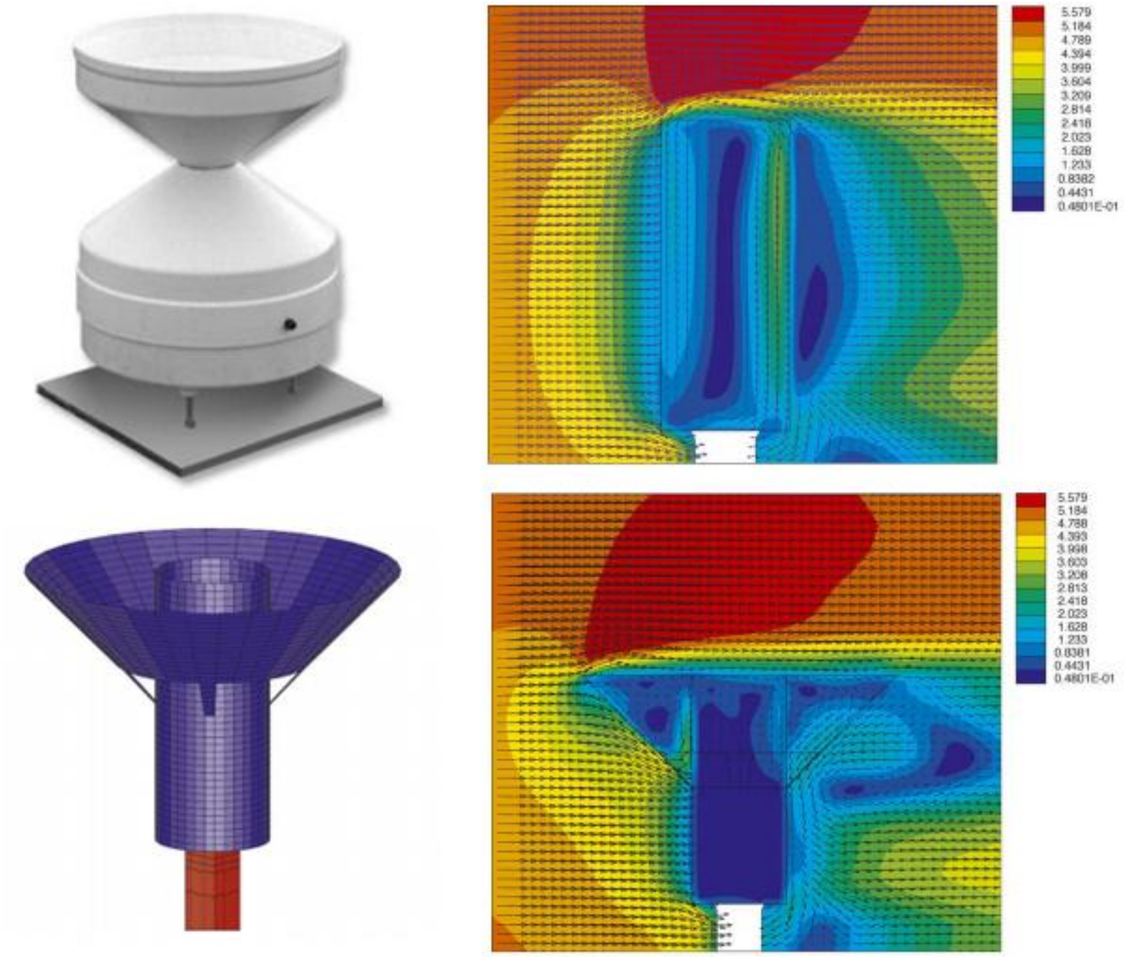


Figure 8: The SMHI gauge with Nipher wind shield (bottom left) and the ARG100 (top left), the wind flow distortion caused by an unshielded (top right) and a shielded (bottom right) Nipher gauge (Michelson, 2004b).

The Michelson (2004) DCM has been tested and calibrated for liquid, mixed and solid precipitation. However, this significantly complicates the process because in the correction procedure for mixed and solid precipitation “gauge coefficients” are needed which are dependent on gauge type. Whilst the Michelson (2004) paper provides these coefficients for a number of gauges the ARG 100 is not among them, therefore to make the analysis more reliable only liquid precipitation is considered. In many studies where no exact description of precipitation type is described, the observations of air temperature may be used as a proxy measurement. In studies such as Yang and Ohata (2001) and Zhang et al. (2004), snow is taken to occur at temperatures lower than -2 degrees centigrade, rainfall at above 2 degrees and mixed precipitation in between. This classification scheme will be used, therefore the data measurements which record a temperature of 2 degrees or less will be filtered out of the analysis.

The difficulty in implementing this DCM lies in obtaining accurate measures of the variables it requires (Michelson, 2004b). The input variables include temperature, wind speed and rainfall intensity (mm/hr). The AWS at Gais Gill provides these measurements so in this particular case the DCM is applied as follows, where P_c is the corrected precipitation, k is the correction factor, P_m is the measured precipitation, P_w is the wetting loss of the gauge, and P_E is the evaporative loss:

Equation 2: Dynamic Correction Model (Michelson, 2004b)

$$P_c = k(P_m + \Delta P_w + \Delta P_E)$$

As discussed, ΔP_w and ΔP_E are gauge constants which have been empirically derived from Michelson's (2004) experiment. From the literature review, it is known that errors due to evaporation and wetting loss are relatively small compared to those for wind. Since the requisite gauge coefficients are not available for the ARG 100 these corrections to measured precipitation are assumed to be negligible. This is another limitation in selecting the Michelson (2004) DCM, however it is the best option given the limited availability of the necessary data.

In determining k, the precipitation phase must be taken into account, so k is different for solid, mixed and liquid precipitation. Since only liquid precipitation is being considered, the correction factor is given by:

Equation 3: Formula for the correction factor *k* in the DCM (Michelson, 2004b)

$$k = e^{(-0.00101\times\ln(I)-0.012177\times v_g\times\ln(I)+0.034331\times v_g+0.007697+c)}$$

where I is the rainfall intensity (mm/hr), v_g is the wind speed (m/s) at gauge height, and c is the gauge coefficient. Again, gauge constant c has been empirically derived for individual gauge types. However, all gauge types for liquid precipitation have the coefficient c as either 0 or -0.05, so in this study the assumption will be made that it is zero.

Although the rainfall intensity measurement which is needed is not directly measured at Gais Gill, this can be derived by the aggregation of sub-hourly measurements to form an hourly estimation in millimetres (mm/hr). As with all meteorological measurements, data with the highest temporal resolution (i.e. 1 minute intervals or higher) will provide the most accurate results. However, for the purposes of this study these rainfall intensity measurements are adequate because they are of sufficiently high-resolution to provide reasonable model input data. The correction procedure was carried out using Excel, and it was possible to graphically display the results of P_c and P_m.

4.1.2. Newton Rigg

Gais Gill was a useful site for a comparison of rain gauge types and a preliminary quantification of undercatch. However a longer dataset was needed for high resolution multi-seasonal scale analysis. Newton Rigg was selected as it is currently a site of scientific interest in the Eden Demonstration Test Catchment (DTC) project, as a result it is easily accessible and analysis of the data record could be useful for a wider purpose in the future.

The site enclosure is situated in a rural lowland part of the Eden and therefore is significantly different to Gais Gill in terms of elevation and exposure. It is located at the bottom of a farmer’s field but is fenced off from livestock. The maintenance and monitoring of this site is also carried out by Newcastle University staff visiting the site regularly to download data. The enclosure in Newton Rigg is equipped with an AWS that monitors a wide range of meteorological variables. Fitted to the AWS data logger is an SBS tipping TBR, and connected to a separate logger is a Casella Cel TBR. The SBS is aesthetically similar to the ARG 100 used at Gais Gill, consisting of a funnel-shaped receptacle. The Casella Cel TBR is cylindrical in shape like many national standard gauges and therefore theoretically should provide more of a physical obstacle to the wind.

Data was collected between October 2010 and July 2012 by the AWS logger, it required considerably more manipulation and synthesis than Gais Gill. Having worked with the record it became evident that there were a number of obvious inaccuracies, discontinuities and general data quality issues. It was possible to locate a metadata file which provided some explanation of the reasons for some of the gaps and errors, however in some cases questionable data was filtered out. Provided this was carried out unanimously for both the SBS TBR and the Casella Cel TBR, the comparison between gauges is not affected. A summary of the metadata are presented in Table 2 below.

A graphical representation of discontinuities and inaccuracies can be found in Figure 9 which accounts for the problems displayed in Table 2. The primary y-axis shows percentage of the maximum possible readings. For a complete month's record the number of readings is either 2880 or 2976 or slightly less in February. It can be seen that 14 months out of a possible 21 have at least 95% complete data record. It can also be noted that the count of the records for the Casella Cel TBR and the SBS are exactly the same. Since both gauges were connected to a separate logger there were some instances where one gauge registered a recording but the other did not. These were simply filtered out so that the total count of readings for each gauge is identical, precisely 43,790.

Also included in Figure 9 on the secondary y-axis is the monthly average wind speed. For months such as April and May 2011 this can be seen to be erroneously high due the low amount of readings. As a consequence any results that display monthly averages only include data for which there were 95% or more readings.

Table 2: Display of metadata problems at Newton Rigg

Date of metadata problem	Reason for problem
01/09/2010 – 01/11/2010	Casella gauge does not record
10/05/2011 – 17/05/2011	Livestock broken into enclosure,
04/04/2011 – 06/05/2011	Rainfall problem with both gauges
29/05/2011 – 28/07/2011	SBS damaged by cows, offline
08/06/2011 – 01/08/2011	SBS not recording
22/05/2012 – 05/07/2012	AWS fallen over

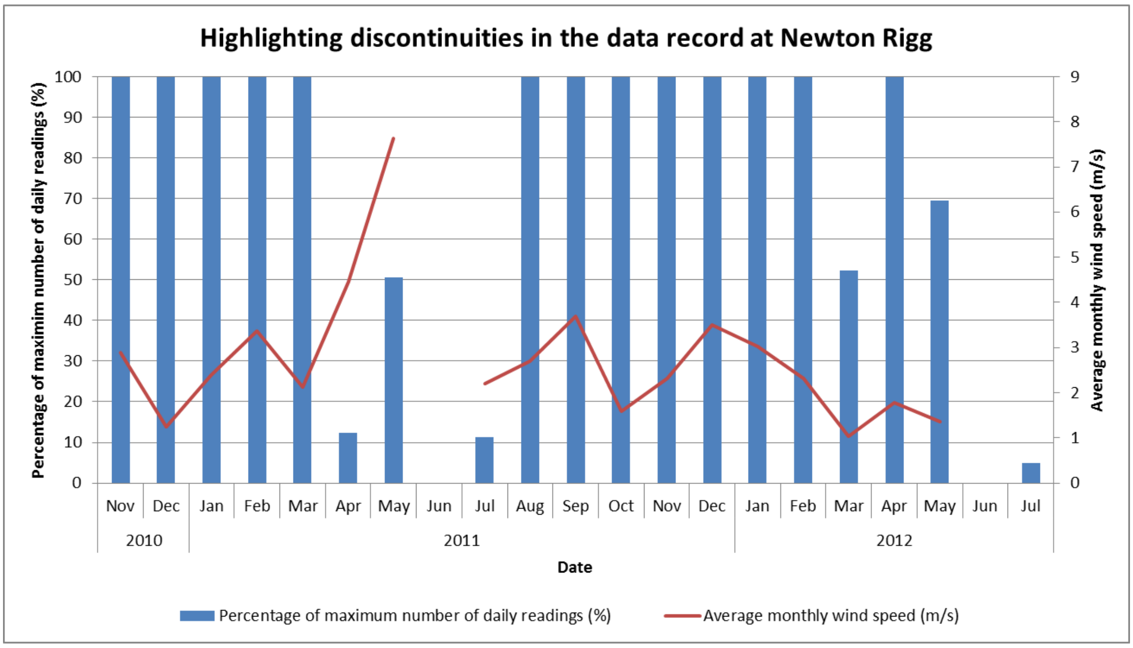


Figure 9: Highlighting discontinuities in the data record at Newton Rigg

Results from Newton Rigg involved a comparison of the total accumulated precipitation between the two TBRs for the duration of the record. This is displayed graphically and is tested for significance again by the use of the paired ‘t’ test. Of particular interest in this case is the explanation of any significant difference between the accumulated catch of the TBRs. The theory has been put forward that the more aerodynamic SBS will catch more than the cylindrical Casella Cel. However, statistically attributing the difference in catch to wind effect or rainfall intensity is a more challenging undertaking than a qualitative theoretical explanation. To do this, it is possible to plot the difference between gauge catch against the wind speed or rainfall intensity. However, due to the quantity of data points there will be a large amount of scatter making it difficult to visually locate any trends. Therefore, by applying regression statistics the P-value can be obtained to test the level of significance.

An estimation of the true precipitation will again be made by using the Michelson (2004) DCM which remains the most applicable technique for this data record. A further graphical representation of the undercatch at different wind speeds according to the DCM can be obtained by plotting the ratio of gauge catch to true catch, against the wind speed. Since the Michelson (2004) DCM includes rainfall intensity as an input variable, it is expected that the ratio of catch will show a wider spread, but still decrease nonlinearly proportional to increasing wind speed.

In May 2012, a partnership was initiated between Newcastle University and Environmental Measurements Limited (EML). EML agreed to install a new range of instrumentation in the enclosure at Newton Rigg. They also volunteered to monitor and download the data for a 12 month period. The new installation can be seen in Figure 10.

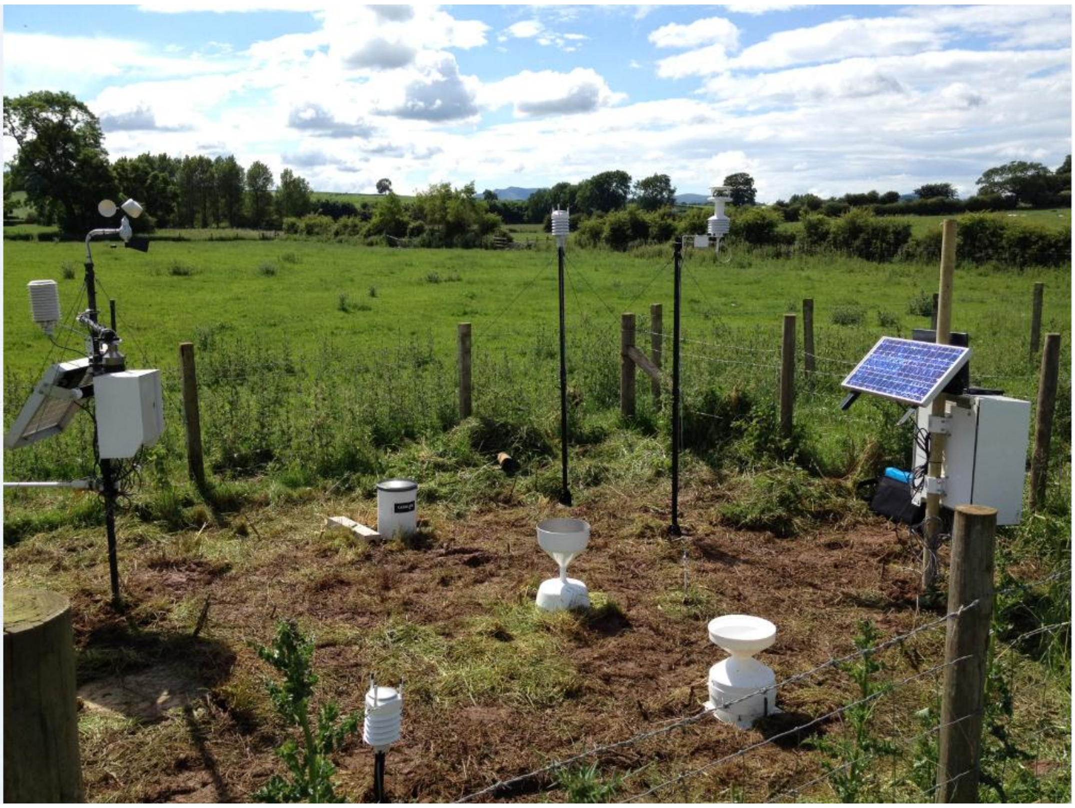


Figure 10: The equipment installed at Newton Rigg from July 5th 2012

Existing at the site prior to the new installation were the AWS and data logger on the black pole to the left of the picture, the Casella Cel TBR on the ground at back of the enclosure (with the piece of wood beside it), and the funnel-shaped SBS in the middle. On July 5th 2012 a number of instruments were added to the existing setup and attached to a new data logger which is on the wooden pole to the right of the enclosure. An additional TBR was introduced, the ARG100 which is similar in design to the SBS. Two Vaisala WXT 520 weather transmitters were installed, one at ground level which can be seen at the bottom of the picture, and one at the top of a 2 metre mast at the back right of the enclosure. In addition, a MetPak II wind sensor was loaned by Gill Instruments and is situated on the 2 metre mast on the right of the enclosure. It was ensured that both weather transmitters and the wind sensor were installed facing north, so that the bearings for wind direction are correct.

Initially, it had been hoped that this installation would be in operational in time to provide several months of comparative rainfall measurements. Unfortunately the installation was delayed a number of times before it was set up at the beginning of July by Mark Dutton (Managing Director, EML) and Michael Pollock (the author). Therefore there is not a large amount of data available, some preliminary comparisons may be carried out if the data can be accessed before the submission of this project. However, the merit of this installation will be justified in a years' time when there will be 12 months of uninterrupted data from a total of five precipitation measuring devices.

This exciting new installation will provide sufficient data for a wide number of experiments. For example, the 3 TBRs situated beside each other will record data at a high time resolution, this will allow for a comprehensive intercomparison study to test which design is best. Furthermore, there will be a great chance to carry out more tests on correction procedures and to refine them. It should also be stressed that there is a unique and tantalising opportunity to install a reference pit gauge here which could be used as the basis from which to develop new correction procedures for each of the instruments. This could begin the process of developing a “Dynamic Correction Model” that is uniquely applicable to these types of instrument.

4.2. Long-term analysis of daily resolution data

Data is retrieved from the British Atmospheric Data Centre (BADC) to perform a long term analysis on precipitation records and apply correction procedures to evaluate the effect of undercatch.

4.2.1. Great Dun Fell

Great Dun Fell is also situated within the Eden catchment, however it differs significantly from both Gais Gill and Newton Rigg. At 868 metres, it contains the highest altitude daily recording rain gauge in England. It is also a unique site because of the strong north-easterly winds that periodically blow down the south-west slope of the Cross Fell escarpment, known as the “Helm wind”. These strong winds make the site extremely suitable for a study of the implications of rainfall undercatch because at very high wind speeds the effects are magnified and therefore easier to detect.

The weather station at Great Dun Fell is within a network operated by the Met Office called the MIDAS Land Surface Stations database. In order to access the data it was necessary to register with the BADC who assist UK weather researchers to locate, access and interpret atmospheric data and ensure its long-term integrity (BADC, 2012). This required a working knowledge of the user interface and the ability to locate and download data, which is achieved by the submission of “requests”. Furthermore, each weather station has different types of data available which are encoded and therefore these require a certain degree of knowledge in order to download the relevant records.

Through further investigation it was discovered that there were two stations on top of the fell, the older starting in 1958 and closing in 2004 (BADC, 2012). The new site was moved 100 metres away and it started operating in 1993. Unfortunately, the new site was not equipped with a raingauge. After some investigation the only time period that had a relatively complete record for both precipitation and wind speed was between 1981 and 2000. This was of sufficient length to justify the “long-term” analysis which was proposed, so the data was downloaded and underwent some standard correction methods to account for any discontinuities in the record.

Precipitation at Great Dun Fell was measured by the UK’s standard national gauge, the Met Office Mk 2. Precipitation and wind speed data is recorded daily, so the high resolution analysis carried out at Gais Gill and Newton Rigg is not possible. A yearly summary of the available record between 1981 and 2000 can be seen in Figure 11, which shows that there were very few missing precipitation data. However, there are a higher proportion of days in each year which are missing average wind speeds.

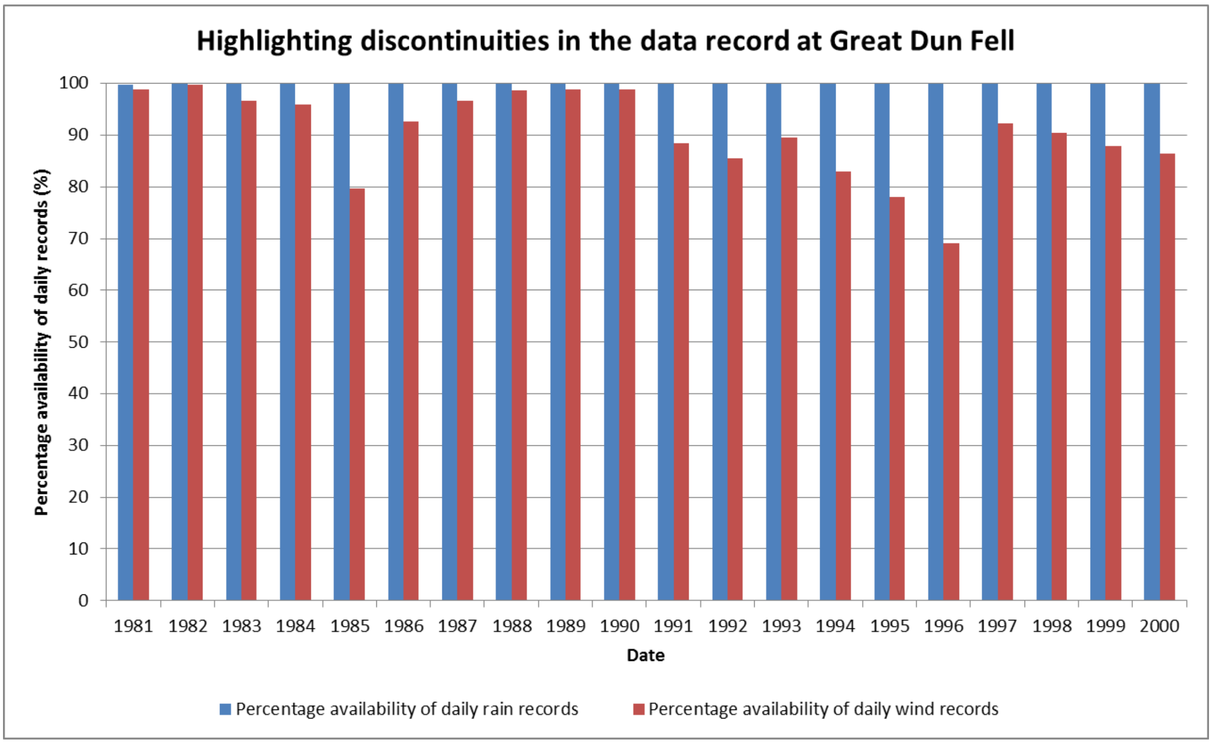


Figure 11: Highlighting discontinuities in the data record at Great Dun Fell

The main reason for studying a highly exposed site such as Great Dun Fell was to apply a correction procedure which would accurately quantify the amount of rainfall lost through undercatch. Both the field and the numerical methodologies in the literature proved that wind induced loss depends mainly on two variables: the wind speed and the microphysical rain structure (i.e., drop size distribution) (Habib et al., 1999). A study by Habib et al. (1999) on the effect of averaging temporal scales on correction procedures shows that the approach for correcting daily precipitation measurements is significantly different and less accurate to those used for correction of measurements with a higher resolution. With the latter there is an abundance of input data such as rainfall intensity and wind speed at gauge orifice and since both are characterised by high temporal variability there are significant differences when correcting for daily or monthly data.

Correcting for daily, monthly or greater timescales requires a derivation of the microphysical rain structure component to enhance accuracy. This must be derived either from data which are more readily available, or interpolated from empirical relationships (field intercomparisons or numerical simulations) built through rigorous testing. In some cases where input data for a correction model are unavailable it is necessary to extrapolate from the empirical relationships by linear regression. For example, if a correction factor (k) has only been developed for measurements recorded up to a certain value of wind speed, it is necessary to use linear regression to derive k-values for higher wind speeds, unless a better model exists.

Due to the unique nature of the Great Dun Fell site, the average daily wind speeds recorded are significantly higher than in any empirical study. Even complex correction procedures based on numerical simulation of wind tunnel tests have not been developed for the very high wind speeds which are present at Great Dun Fell. Some empirically based models have been developed for correcting precipitation in high wind speeds but these are generally for high latitudes where snow is the dominant form, and correcting for snow is completely different and more challenging than correcting for rainfall. In addition, these studies are generally based on the national standard snow-measuring gauge in whichever country they are developed, which are completely different to the UK MO Mk 2 at Great Dun Fell.

With data of daily resolution, some precipitation correction procedures have been developed purely on the basis of wind speed, such as Yang et al. (1998) and Legates and DeLiberty (1993). However, a study conducted by Habib et al. (1999) categorically states that rainfall measurements cannot be described as a function of wind speed only, and emphasises the importance of rainfall intensity and the drop size distribution. This was also reported by Sevruk and Hamon (1984) who noted that a relationship between the correction factor and the wind speed only, shows a large scatter. They introduced an additional input parameter that is related to the rainfall structure and can be computed on the basis of the proportions of the small rainfall intensity (Habib et al., 1999).

The work carried out by Sevruk and Hamon (1984) was augmented and reported as a comprehensive correction procedure in Sevruk (2006). Due to data availability and the reviews of this correction procedure, it was selected for use at Great Dun Fell. It was developed for monthly correction of precipitation measured by the Hellman gauge situated at least one metre above the ground. Since Great Dun Fell uses the UK MO Mk 2 and it is situated at ground level, these are limitations. In addition, it requires reliable, homogeneous datasets without gaps, and this criterion is fulfilled by Great Dun Fell's record. It has also been developed for sites where evaporation losses can be neglected and snowdrift and splashing are not of major importance (Sevruk, 2006). Note that the model also has a solid and mixed precipitation correction component to consider, however as this is outside the scope of the current study only rainfall will be included. The assessment will be achieved in the same way as it was for Newton Rigg, where average daily air temperatures which fall below 2 degrees Celsius are filtered out in accordance with Ye et al. (2004).

The corrected sum of monthly precipitation can be calculated according to Sevruk (2006) and is shown in Equation 4, where N_k is the corrected monthly precipitation (mm), k is the wind related conversion factor, N_g is the measured monthly precipitation (mm) and ΔN_{2-3} are the wetting losses of the gauge.

Equation 4: Correction procedure according to Sevruk (2006)

$$N_k = k\ (N_g +\ \Delta N_{2-3})$$

Wetting losses are dependent on the type of precipitation and are calculated by using the fraction of snow on total precipitation. However, since snow is considered outside the scope of this study ΔN_{2-3} can be considered a constant which can be derived from Equation 5:

Equation 5: Wetting losses for the Hellman gauge (also applied to the Mk 2 gauge in this instance)

$$\Delta N_{2-3} = 0.30q\ (2 - \left(\frac{Q}{100}\right))$$

where q is the number of precipitation days, Q is the fraction of snow (%) and 0.30 is the mean daily wetting loss in millimetres for rain. Values for k can be taken from Table 3, they have been experimentally derived and can be interpolated linearly (Sevruk, 2006).

Table 3: Sevruk (2006) wind-induced correction factor ‘k’ for the Hellman gauge

	u_{hp} (m/s)							
	0.5	1	1.5	2	2.5	3	3.5	4
N'0.3	*k*-values for rain (linear interpolation possible)							
20	1.010	1.015	1.020	1.015	1.020	1.030	1.035	1.040
30	1.010	1.015	1.015	1.020	1.025	1.035	1.040	1.050
40	1.010	1.015	1.015	1.025	1.030	1.040	1.050	1.060
50	1.010	1.020	1.025	1.040	1.045	1.055	1.065	1.075
60	1.010	1.020	1.030	1.040	1.050	1.060	1.070	1.080
70	1.010	1.020	1.030	1.045	1.055	1.065	1.075	1.085
80	1.011	1.026	1.031	1.046	1.056	1.071	1.081	1.091
90	1.011	1.026	1.036	1.051	1.061	1.081	1.086	1.096
100	1.011	1.026	1.036	1.051	1.061	1.086	1.091	1.101

The rain structure parameter $N'_{0.3}$ can be calculated as shown in Equation 6, where N is the measured monthly precipitation amount (mm), T is the monthly air temperature (°C) and q is the number of precipitation days per month.

Equation 6: Rainfall structure parameter (Sevruk, 2006)

$$N'_{0.3} = 145 - (53 \times \log(T \times \frac{N}{q}))$$

Unfortunately, this daily correction procedure has a major limitation dramatically affecting the validity of results. The wind related conversion factor (*k*) is taken from Table 3 which has used empirical testing to calculate the ‘*k*’ values for wind speeds for every 0.5 m/s up to 3.5 m/s. Whilst values can be calculated for wind speeds lying between these set measurements by linear interpolation, it is more problematic to consider values outside of this range. The only option available is to extrapolate the data and use the resulting linear regression equation to calculate each ‘k’ value. Factoring in the different rainfall structure parameters (N values) improves the accuracy of this model, but only for one of these N values does the linear regression equation fit the data completely (i.e. $R^2 = 1$). Therefore, for rainfall structures which have an R^2 value which does not equal 1 there is a systematic error that the regression equations incorporate. Figure 12 is a chart showing the ‘k’ value plotted against wind speed. Also shown are the different rain structure parameters between 20 (bottom line) and 100 (top line). The lines on the chart represent the linear regression of each of these rain structure (N) parameters.

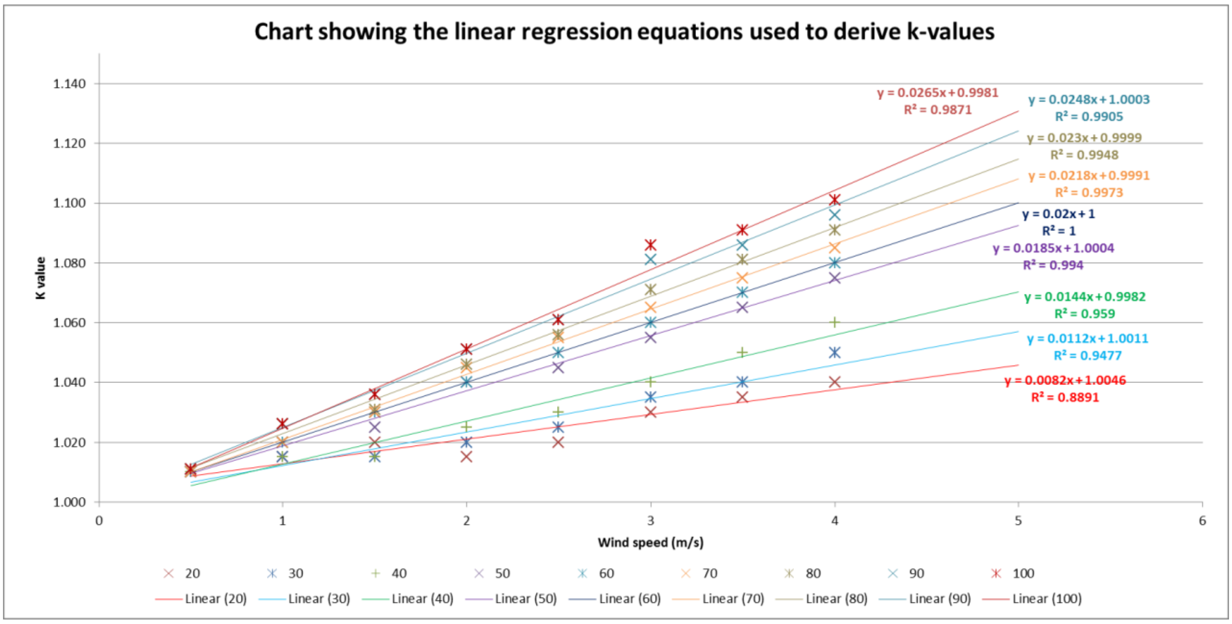


Figure 12: Showing the linear regression equations used to derive the conversion factor k using the Sevruk (2006) correction procedure

Figure 13 shows plots for a correction factor derived in numerical methodologies by Habib et al. (1999). The ‘k’ values in this case represent different drop size distributions, k= -1 for orographic rain; k=2 for thunderstorm rain and k = 4 for showers. The high non-linear variation of the correction factor with the wind speed, rainfall rate, and the drop size distribution shows the complex behaviour of the wind effect and its multidimensional dependence on the various wind and rainfall characteristics (Habib et al., 1999). Furthermore, raindrops adjust their trajectories to wind gusts quickly, and therefore following the temporal variability of the wind is the most crucial aspect of a successful application of a correction procedure (Habib et al., 1999), this is evidently is very difficult with only daily data available.

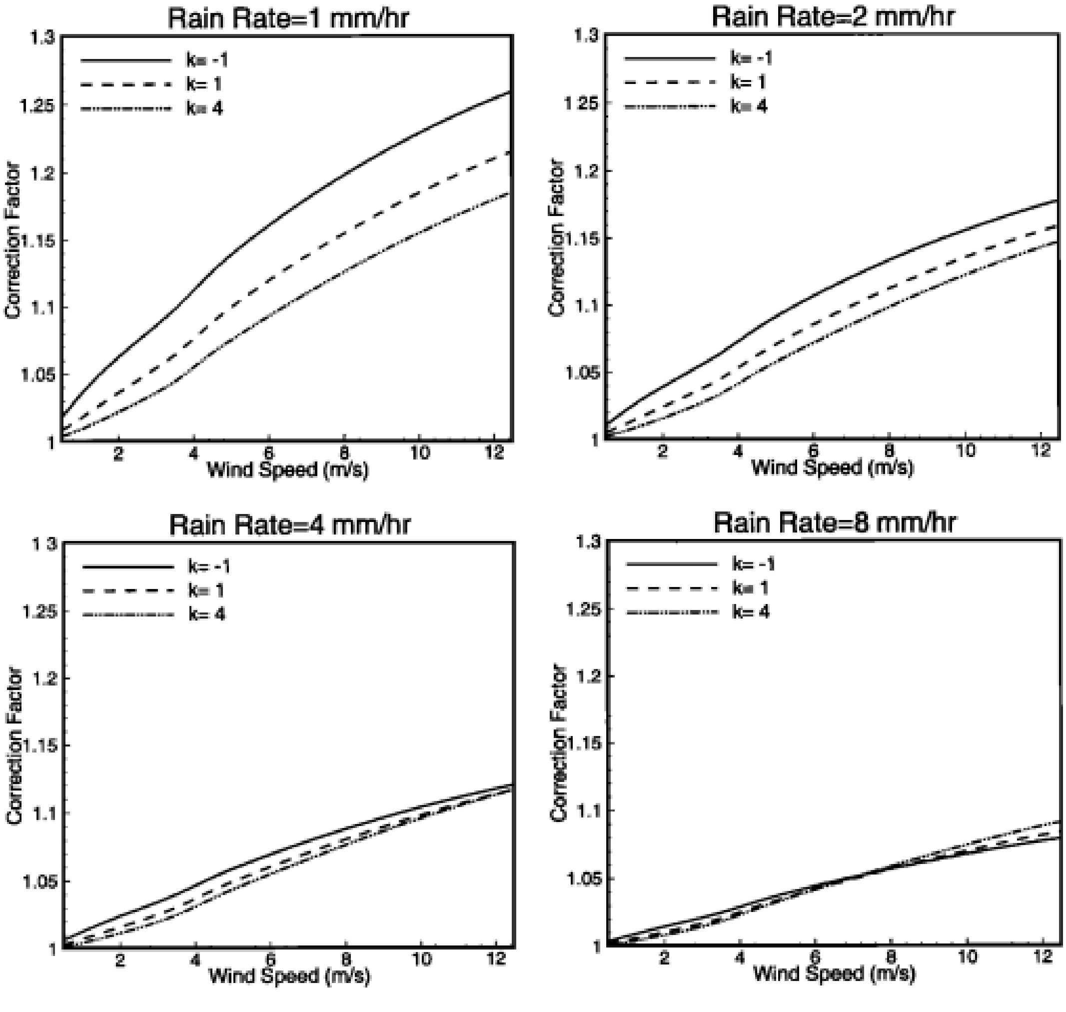


Figure 13: Plots of the numerically simulated correction factor defined by Nespor and Sevruk (1999) as a function of wind speed, rainfall rate, and a drop size distribution parameter k (Habib et al., 1999)

It has been established that wind-induced error increases nonlinearly with the correction timescale. The increase of the correction timescale leads to an overestimation of the wind-induced error. If the measurements are corrected on a daily timescale instead of hourly, the wind induced error could be overestimated by a factor of about 2-3 times (Habib et al., 1999). The error estimation gets as high as 5 times if the corrections are performed on the monthly scale, which shows the vital need for refinement of existing correction procedures in order to obtain reliable and unbiased rainfall estimates (Habib et al., 1999).

The purpose of the previous few paragraphs was to justify the case for selecting the best correction procedure available for Great Dun Fell's daily resolution data. However, it was also necessary to clearly display and comment on the severe limitations by augmenting the arguments laid out in the literature review on the inadequacy of current methods of precipitation correction. Sevruk's (2006) correction procedure may be the best available, but it is still susceptible to a very large degree of uncertainty. This brief analysis serves to highlight the importance of work which still needs to be done on developing an adequate correction procedure for the UK's hydrological monitoring network. This argument will be put forward in detail during chapter 6.

After the calculation of the correction factor, a "true" precipitation value is presented with the original measured precipitation to form a comparison. Most of the analysis concerns the summer months because precipitation, more than likely, falls as liquid during this season. The difference between measured precipitation data and corrected precipitation data is discussed.

The assumption is made that whilst the corrected data has many limitations, it is still a better estimate of true precipitation than the original measured data. Given a notable difference between corrected and true precipitation, it is interesting to study the corrected data for “trends” which may be found in the record. For instance, one of the hypotheses of this project proposes to investigate whether an apparent change in measured precipitation could be explained by observed changes in temperature or wind speed. For example, a gradual increase in temperature at the site may change a proportion of the annual precipitation from snow to rain. The amount may not appear to be much, but undercatch is significantly greater for snow than for rain, especially in high wind speeds, which would mean that the actual measured quantity is significantly more than would have been collected if the precipitation fell as snow. The implications of this would indicate an apparent increase in precipitation based on the measured values, which may not be the case in reality.

4.2.2. Valley

An extensive search of the UK’s climate stations was carried out in an attempt to find somewhere with a long record data record to provide context and validity for a study of climate. Furthermore, a site which was less subject to the wind and temperature extremes of Great Dun Fell would benefit analysis. Valley is a site found in western Wales close to Holyhead. Since it is coastal and of low elevation it is subject to milder winters than Great Dun Fell, meaning variations in winter rainfall may be studied. Valley has a near complete record from between 1961 and 2008.

5. RESULTS

Results for this project are formed from a number of different strands. High resolution analysis of Gais Gill and Newton Rigg provides the context to study the relative merits of different rainfall measuring instruments. Statistical analysis provides a method of testing the significance of findings. Knowledge collected from literature is applied to enrich analyses. The sites of Great Dun Fell and Valley provide the context for a number of long-term analyses.

5.1. High resolution analysis: Gais Gill

The site at Gais Gill provides a unique opportunity to test new instrumentation against conventional measurement methods. A previous study compared these instruments at the event scale showing some interesting findings, but no statistical significance was attributed to these results.

5.1.1. Testing conventional instrumentation against new methods

Data recorded at Gais Gill was filtered to include only readings which occurred at an air temperature of 2°C or higher (Ye et al., 2004). Figure 14 shows the percentage of the total monthly precipitation data which were recorded above this temperature threshold. This is expressed as a percentage of the total recorded data shown in Figure 7 in chapter 4. With air temperatures above 2°C precipitation events are “extremely likely” to include only rainfall (Ye et al., 2004). Over 80% of recorded measurements occurred at temperatures of 2°C or more in October. On the other hand, in December 2010 only 20% of the recorded measurements were above 2°C. Overall, of the data which was recorded by both gauges, 47.23% of it registered above the temperature threshold. All analyses for Gais Gill occur using the data presented in Figure 14.

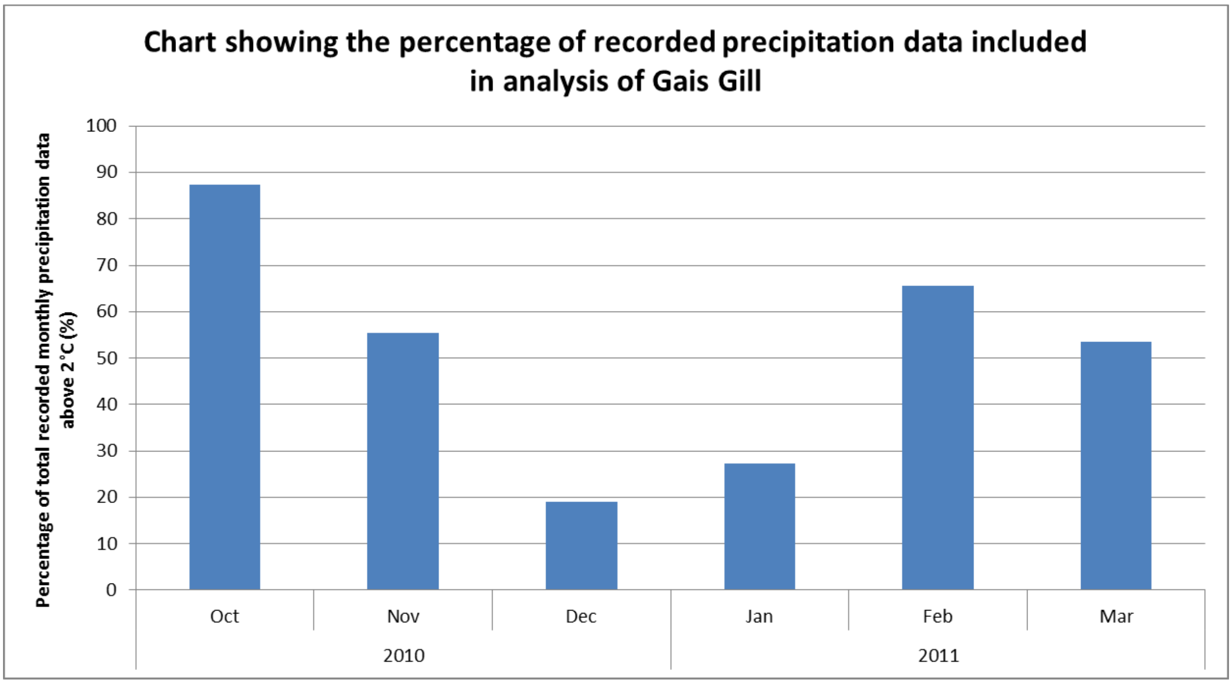


Figure 14: Chart showing the percentage of monthly data which was recorded above the 2°C temperature threshold at Gais Gill and is therefore classified as rainfall

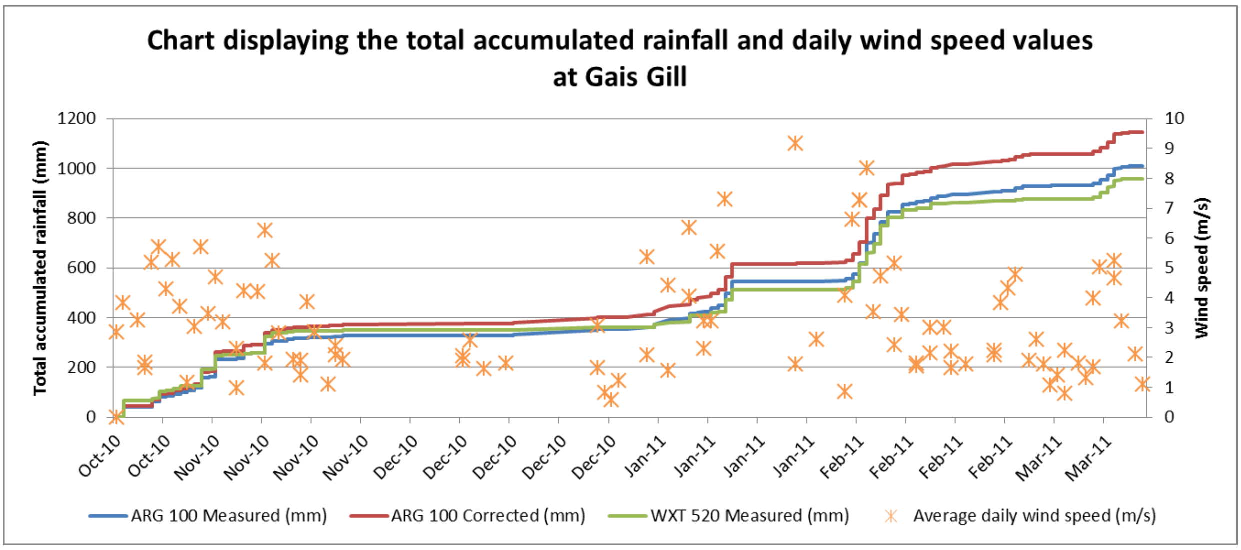


Figure 15: Total accumulated rainfall collected by the ARG 100, the WXT 520 and the DCM corrected value

Figure 15 shows the accumulated rainfall at Gais Gill as recorded by the ARG 100 TBR and the WXT 520. Also marked as the red line is the Michelson (2004) DCM corrected precipitation value applied at a sub-hourly resolution timescale to the ARG 100. The orange scatter shows the daily wind speeds.

Application of a paired ‘t’ test with the measurements from the two instruments as input variables returns a ‘p’ value of 0.42 which signifies that there is no significant similarity between the readings for each. Pollock (2011) showed that when this data was studied at the event-scale there are some interesting results, however with such a short data record it is not possible to draw meaningful conclusions irrespective of statistical analysis.

5.1.2. Applying a high resolution correction model

Figure 16 shows the monthly rainfall totals for the ARG 100 tipping bucket rain gauge, the WXT 520 impact disdrometer and the corrected ARG 100 rainfall record according to the Michelson (2004) DCM. No widely available wind correction procedures have yet been developed for rain accumulation for the impact disdrometer so none could be applied in this analysis. Also displayed on a secondary axis is the average monthly temperature and average monthly wind speed.

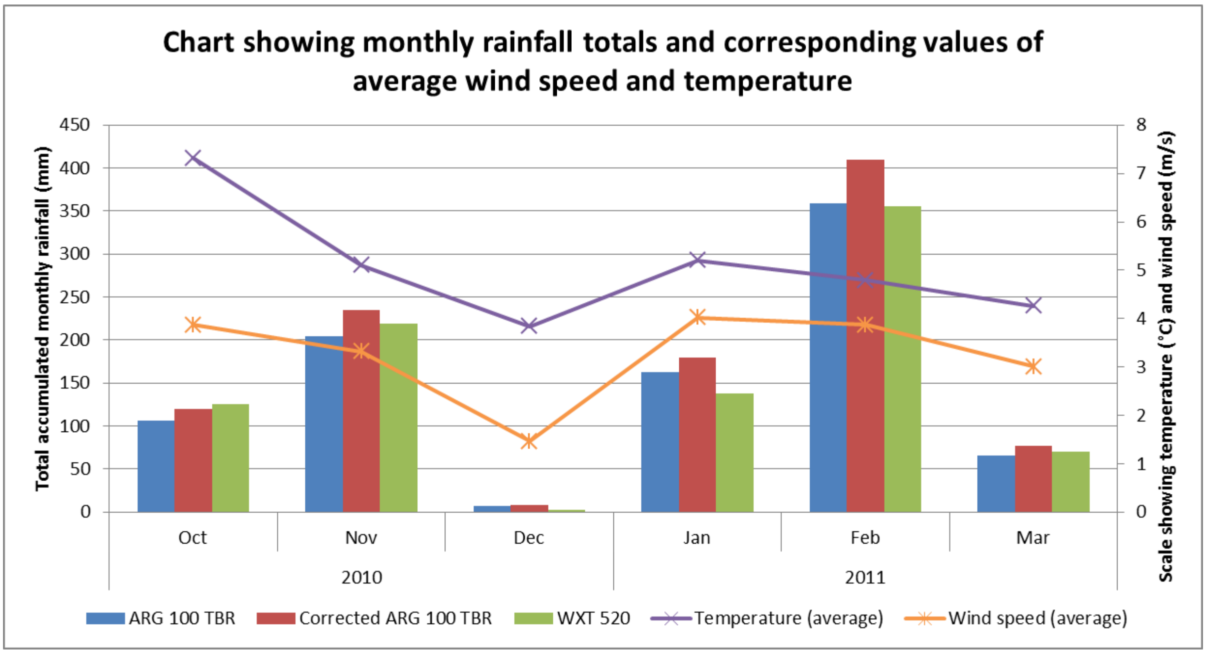


Figure 16: Chart showing monthly rainfall totals for the ARG 100, the WXT 520, and the Michelson (2004) correction applied to the ARG 100. Also shown is the average monthly temperature and wind speed.

Table 4 provides a quantification of the monthly undercatch according to the Michelson (2004) correction procedure. The winter months of December and January appear to have less modelled undercatch than the late autumnal and early spring months.

Table 4: Monthly undercatch percentages produced by the DCM

Year	Month	Undercatch of
2010	Oct	15.9
	Nov	14.2
	Dec	10.7
2011	Jan	12.6
	Feb	14.6
	Mar	17.0

5.2. High resolution analysis: Newton Rigg

The site at Newton Rigg presented an interesting opportunity to compare the relative merits of two differently designed tipping bucket raingauges. The SBS is similar in shape the ARG 100 which was is situated at Gais Gill, therefore it is designed to minimize disruption to the surrounding wind field. The Casella Cel is similar in appearance to the UK MO Mk 2 national standard gauge in that it is cylindrical in shape.

5.2.1. Comparison of tipping bucket raingauges

Figure 17 shows the percentage of recorded data which were above the 2°C temperature threshold signifying that the registered precipitation is rain. This is expressed as a percentage of the total recorded data shown in Figure 9 in chapter 4.

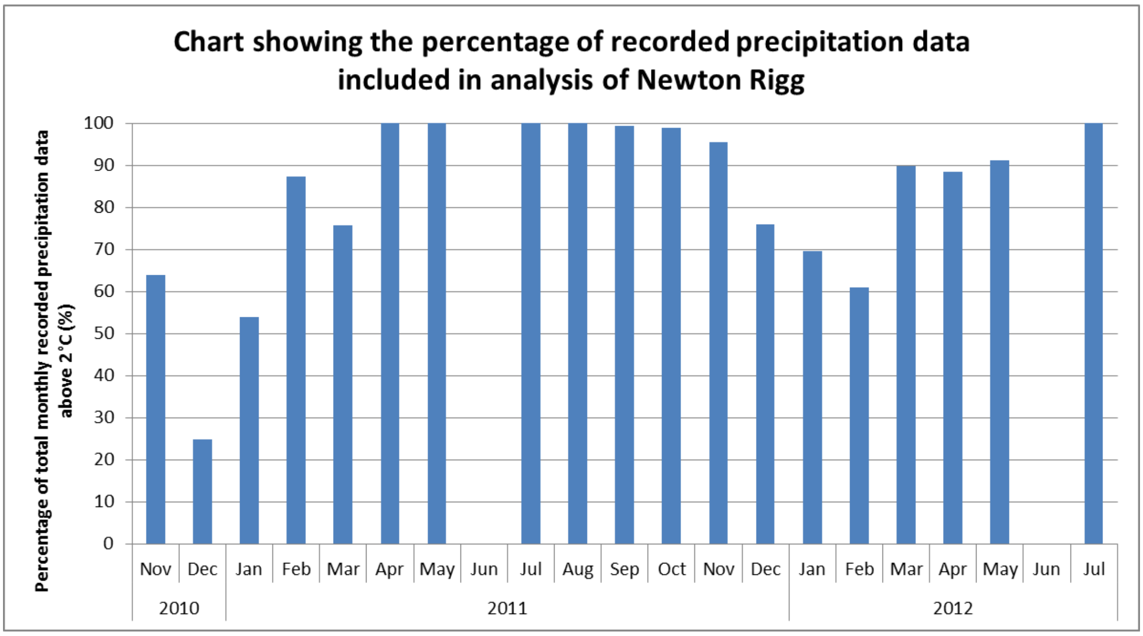


Figure 17: Chart showing the percentage of monthly data which was recorded above the 2°C temperature threshold at Newton Rigg and is therefore classified as rainfall

Figure 18 shows the total accumulated rainfall recorded by each TBR at Newton Rigg. The green colour between the lines aims to graphically show the gradual increase in difference over time. The white gaps between this green colour represent periods for which data was not recorded or discounted due to issues of quality.

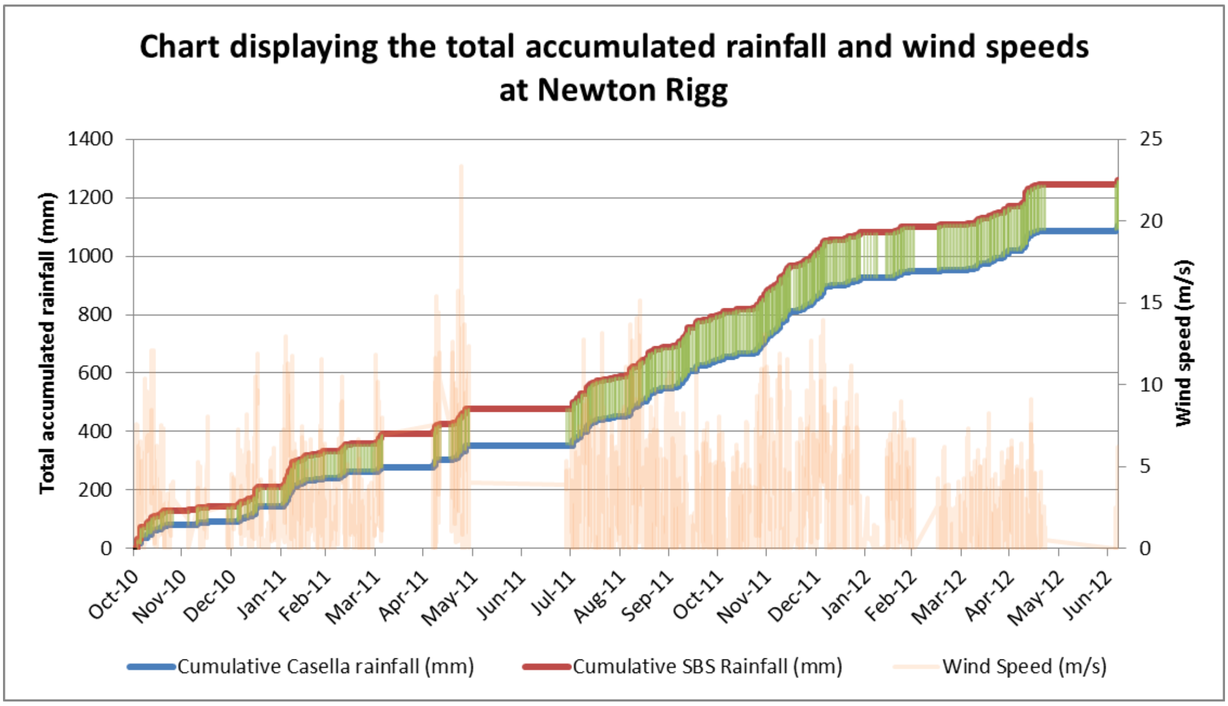


Figure 18: Total accumulated rainfall recorded by each tipping bucket rain gauge.

Table 5 shows the monthly totals of rainfall recorded by the two TBRs. Also noted is the percentage difference between these, and the average wind speed during each month. The grand total for the entire record is shown at the bottom of the table.

Table 5: Monthly rainfall totals as recorded by the TBRs, and their difference expressed as a percentage

Year	Month	Casella rainfall (mm)	SBS rainfall (mm)	Percentage difference (%)	Average wind speed (m/s)
2010	Nov	79.1	130.6	39.43	3.569
	Dec	11.6	13.2	12.12	2.120
2011	Jan	54.4	66.6	18.32	3.382
	Feb	96.6	121	20.17	3.534
	Mar	21.8	30.8	29.22	2.631
	Apr	14	29.6	52.70	4.461
	May	75.5	87.4	13.62	7.630
	Jun				
	Jul	0	0	0.00	2.203
	Aug	99.2	108.4	8.49	2.700
	Sep	95.2	99.8	4.61	3.717
	Oct	98	111.2	11.87	1.604
	Nov	77	81.2	5.17	2.431
	Dec	132.8	133.6	0.60	4.225
2012	Jan	70	66.8	-4.79	4.154
	Feb	21.6	21.8	0.92	3.251
	Mar	6.4	6.2	-3.23	1.154
	Apr	64.8	62	-4.52	1.857
	May	69	74.4	7.26	1.496
	Jun				
	Jul	16	16.2	1.23	2.001
Grand Total		**1103**	**1260.8**	**12.52**	**3.037**

5.2.2. Statistical testing of results

It is possible to carry out a simple student's 't' test for paired samples, with the TBRs as input variables to assess whether there is a significant difference between the recorded amounts of each TBR. This test returns an extremely small 'p'-value in the order of $1x10^{-10}$, showing that there is a highly significant difference in the measurements of the two gauges.

Having established that there is a significant difference between the total accumulated rainfall in each gauge, the challenge lies in attributing the reasons for this to a specific factor. From the literature the effect of wind speed and rainfall intensity on gauge catch are well documented. Theoretically, it should be possible to test this using the results from Newton Rigg by plotting the difference in gauge catch against wind speed or rainfall intensity and assessing the relationship. In the case of rainfall intensity, the averaged Casella CEL and SBS value is used. Due to the high level of scatter it is difficult to draw any meaningful conclusions from these residual plots, but applying simple regression statistics returns interesting results. The 'P' value is 0.01 for wind speed and in the order of $1x10^{-33}$ for rainfall intensity. This shows that there is a very small but highly significant relationship between wind speed and rainfall intensity, and the difference in catch between gauges.

Some early correction factors such as Larson and Peck (1974) proposed wind induced loss was a subject to a linear relationship between decreasing gauge-catch and increasing wind speed. It has since been proven that the relationship is non-linear and that the microphysical structure of the rain also affects the wind induced loss. Figure 19 shows a scatterplot of the ratio of gauge catch to true catch against wind speed. This has been plotted using the Newton Rigg dataset and the Michelson (2004) correction factor. It can be seen that there is an increasing envelope of uncertainty in true catch with increasing wind speed. This is due to the microphysical structure of the rain, or more specifically in this case, the rainfall intensity. For instance, in wind speeds of 13 m/s it can be seen that depending on the rainfall intensity, the ratio of gauge catch to true catch is between 0.5 and 0. 84.

5.2.3. Correction procedures

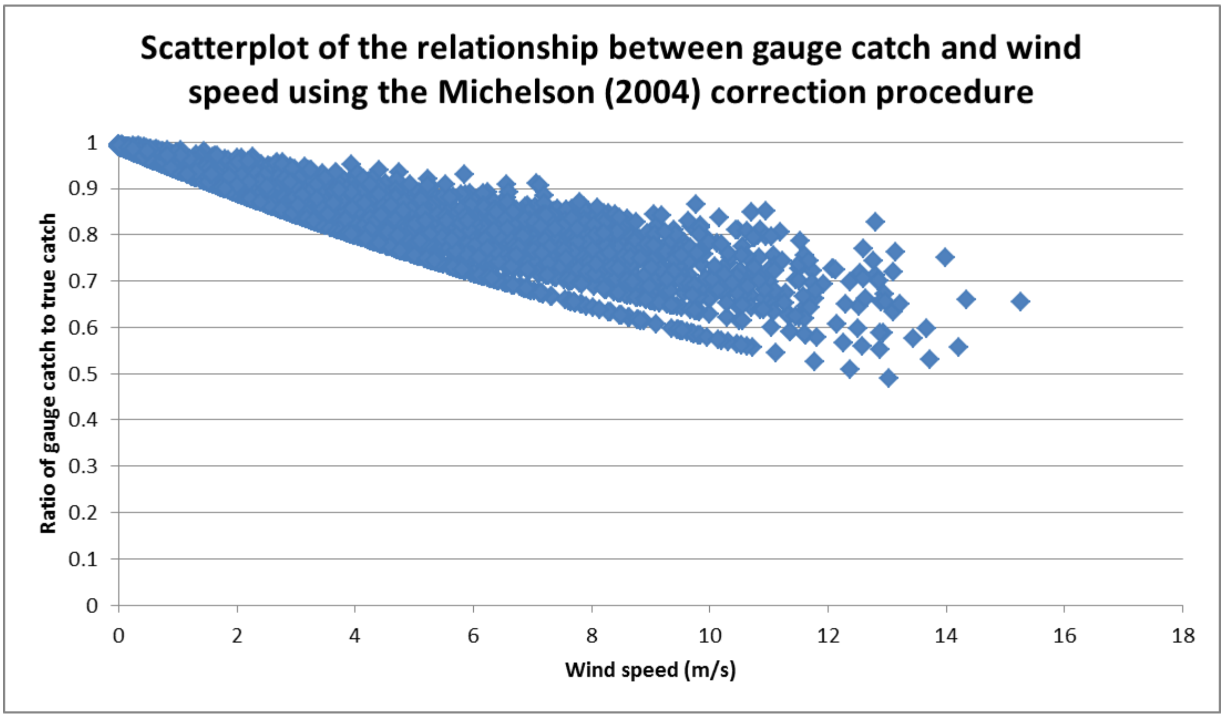


Figure 19: Scatterplot showing the relationship between gauge catch and wind speed using the DCM

As the Michelson (2004) DCM is calibrated for a cylindrical gauge with a funnel-shaped wind shield to reduce the distortion of the surrounding wind field, it will again be applied for the SBS which is the more aerodynamic TBR. It has also been applied to the Casella, but without knowing the actual “true” precipitation (i.e. that which would be recorded by a pit gauge) there is no merit in showing this. Figure 20 shows the values of monthly precipitation for the Casella and the SBS, also shown in green is the total corrected monthly values according to Michelson (2004).

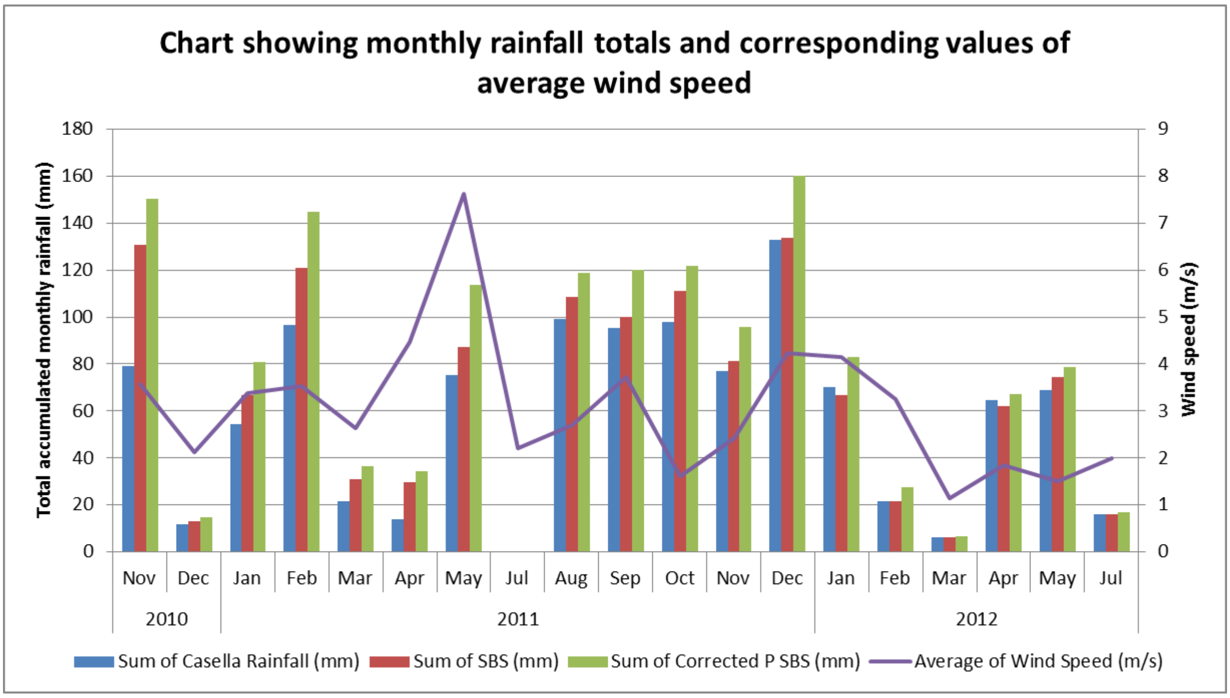


Figure 20: Monthly totals of accumulated rainfall and the DCM corrected value

The total accumulation of rainfall according to the Michelson (2004) DCM for the entire data record was 1470.74 mm. This would suggest that the Casella Cel is undercatching by a total of 25%, and the SBS is undercatching by 14.3 %. As there is no pit gauge in place there is unfortunately no method of verifying the accuracy of this correction model.

Table 6: Monthly values of undercatch produced by the DCM

Year	Month	Undercatch of rainfall (%)
2010	Nov	13.0
	Dec	11.9
2011	Jan	17.6
	Feb	16.3
	Mar	15.2
	Apr	13.5
	May	23.1
	Jul	-
	Aug	8.6
	Sep	16.9
	Oct	8.5
	Nov	15.1
	Dec	16.5
2012	Jan	19.6
	Feb	20.4
	Mar	5.7
	Apr	7.8
	May	5.7
	Jul	3.2

5.2.4. New installation at Newton Rigg and links with EML

Due to the late installation date of the new densely instrumented enclosure at Newton Rigg it has not been possible to perform any meaningful analysis due to the short length of the record. However, the merit of this installation will be justified by summer 2012 when detailed analysis of a year- long record can be carried out. Mark Dutton and EML must be strongly commended for the important role they played in the setting up of this dense instrument network.

5.3. Long-term analysis: a correction procedure for Great Dun Fell

Figure 21 demonstrates the quantity of yearly readings which were greater than the temperature threshold of 2°C which ensures liquid precipitation. It was also assumed that most of the precipitation falling in winter months would be below this threshold and fall as snow. Therefore, for the purposes of studying Great Dun Fell only the summer months of June through to August are used to ensure continuity in the dataset.

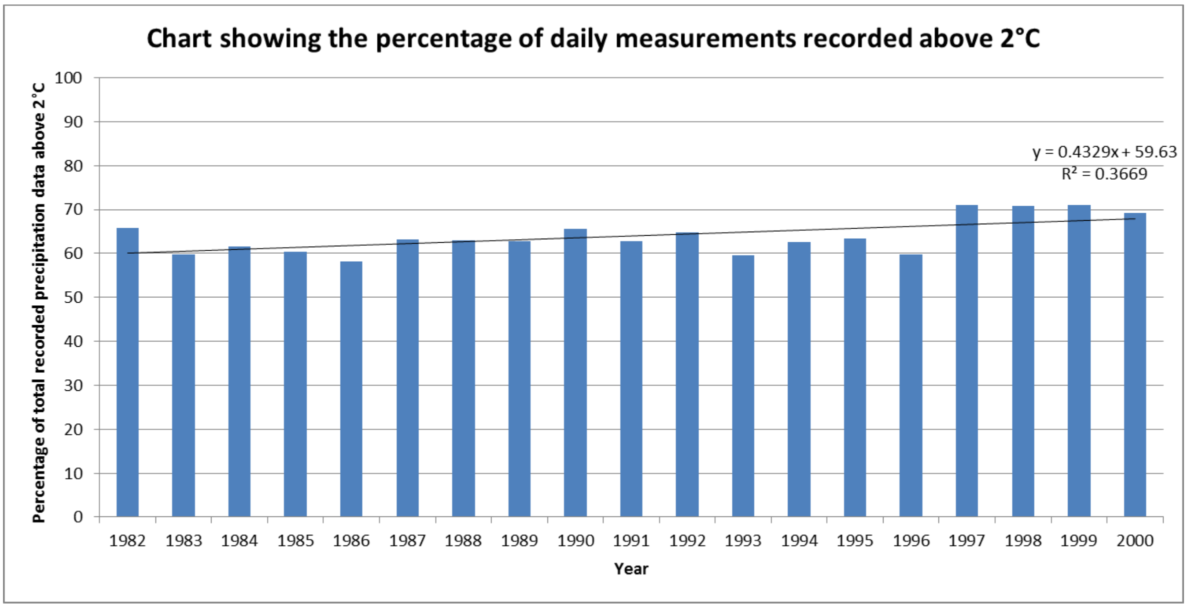


Figure 21: Annual percentage of daily measurements which were recorded above the 2°C threshold which ensures liquid precipitation

The long-term analysis focuses on correction of the rainfall record using the Sevruk (2006) correction procedure to assess the amount of undercatch. The correction model is designed to be applied at a monthly timescale. Figure 22 shows the comparison between measured and corrected rainfall annually for the months of June through to August. It can be seen that according to the Sevruk (2006) model there is a large amount of undercatch. In 1987 the model produces a value of 20% undercatch at Great Dun Fell between June and August. The highest modelled amount of undercatch was 31% in 1995.

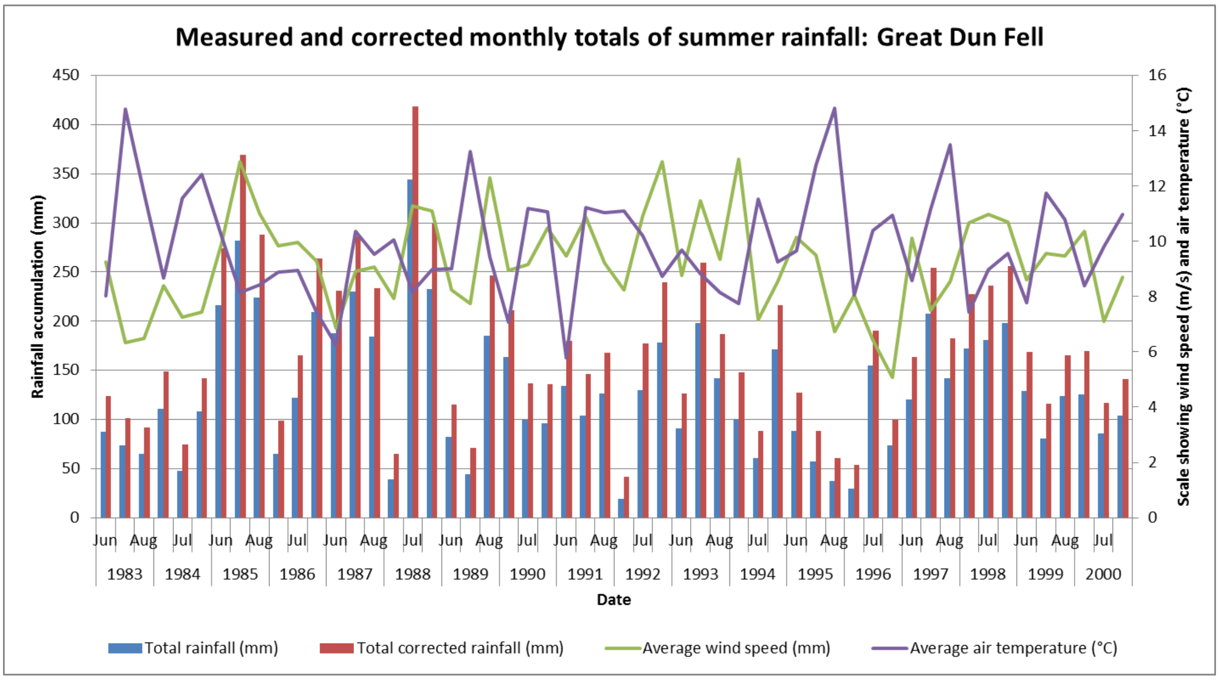


Figure 22: Measured and corrected monthly totals of summer rainfall at Great Dun Fell, also showing the natural variation in wind speed and air temperature.

Table 7 shows the average undercatch for the summer months between 1983 and 2000. Also shown is the average monthly wind speed and air temperature for this period.

Table 7: Average monthly undercatch between 1983 – 2000 for Great Dun Fell according to Sevruk's (2006) correction model

Month	Average undercatch between 1983-2000	Average wind speed (m/s)	Average air temperature (°C)
Jun	29.8	9.3	8.5
Jul	26.5	9.2	10.7
Aug	25.0	9.2	10.4

5.4. Effect of temporal averaging

From the literature review the effect of temporal averaging on the estimation of wind induced loss was notable, but it was interesting to consider the implications of this effect on real correction models such as the Michelson (2004) DCM. Figure 23 demonstrates through the use of field collected data the reported effect of temporal scale on data collected at Gais Gill (Habib et al., 1999). The result of using daily data to produce monthly averages as input data for the correction model can be compared to the effect of using high resolution sub-hourly data to derive monthly averages. It can be seen that both the model precipitation output and the average monthly wind speed are affected by this temporal averaging. Table 8 quantifies this variation in terms of millimetres of rainfall. Further discursive comment is made in chapter 6.

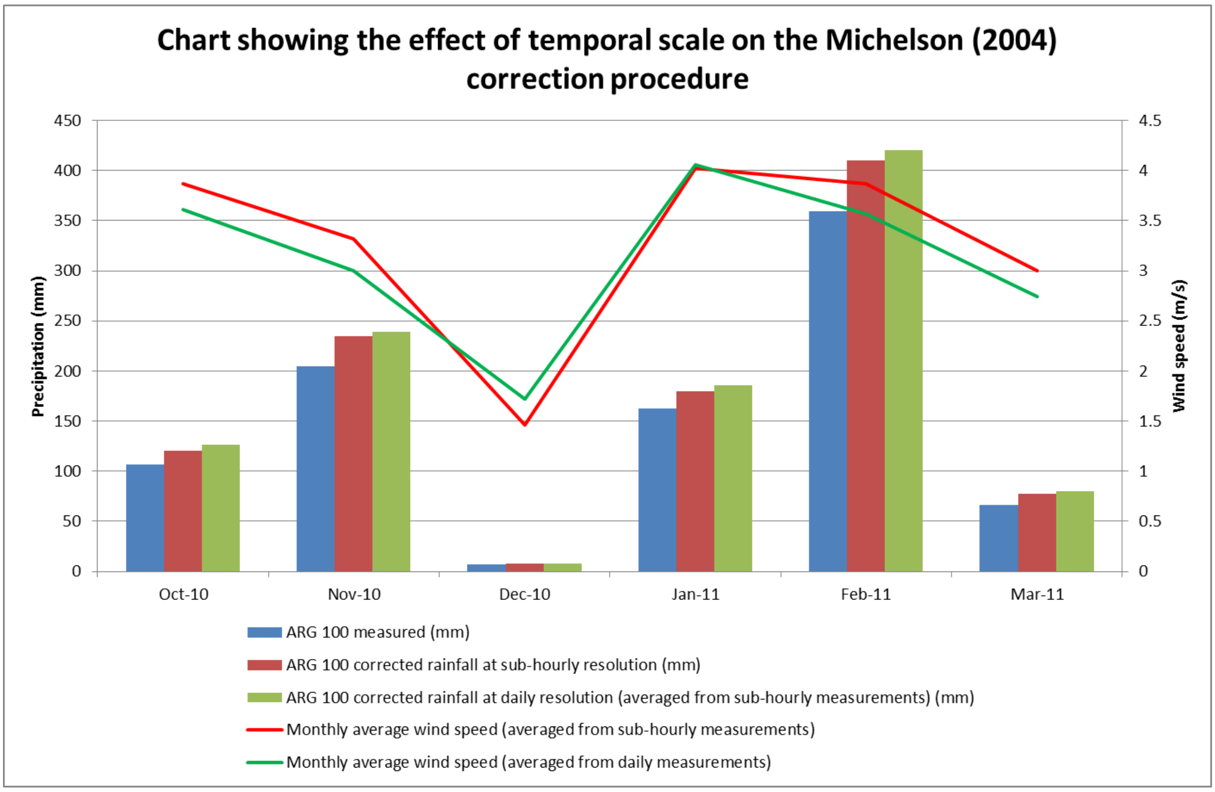


Figure 23: The effect of temporal averaging on wind induced loss by applying a sub-hourly correction and a daily correction to Gais Gill data and comparing the difference

Table 8: A quantification of the effect of temporal averaging on real field data

	ARG 100 measured rainfall	ARG 100 rainfall corrected at sub-hourly resolution	ARG 100 rainfall corrected at daily resolution
Total accumulated precipitation (mm)	**906.2**	**1029.787**	**1059.177**

5.5. Long-term analysis: climatic trends

This section investigates the hypothesis that apparent changes in measured precipitation could be explained by observed changes in variables such as wind speed or air temperature. The effect of correction on observed temperature trends is also considered.

5.5.1. Great Dun Fell

The hypothesis was formed that recorded rainfall may be sensitive to other meteorological variables such as wind speed or air temperature due to the potential implications which a resultant increase in undercatch would have. Thorough analysis of the dataset was initiated to look for any signs of a trend in wind speed above a certain threshold on rain days during the summer months, as well as a trend in air temperature on rain days. The analysis was carried out for the summer months (including September).

Figure 24 shows the results which were found, the implications of which are further discussed in chapter 6.

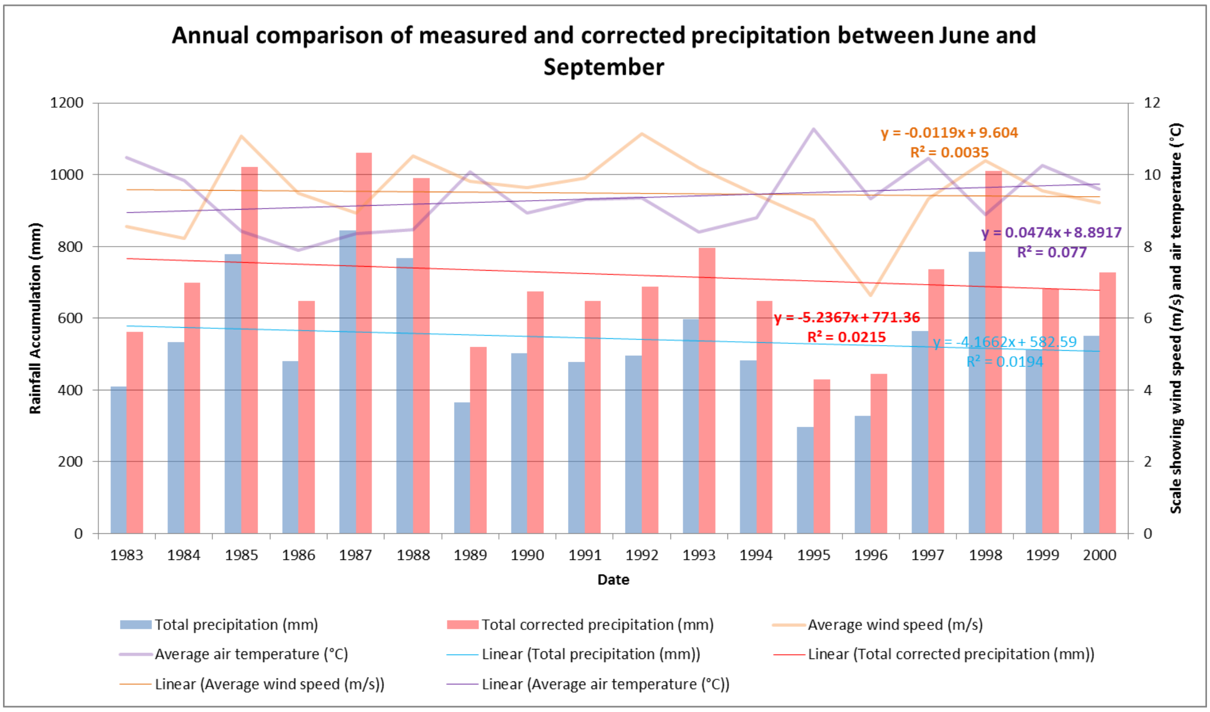


Figure 24: Comparison of measured and corrected precipitation between June and September with linear regression equations

Studying rainfall trends at Great Dun Fell met with a significant number of limitations. The data record was not long enough to produce any meaningful results, any trends which may be found could be as a result of a multi decadal natural variation. Furthermore, the high altitude causes significantly lower than average temperatures all year round, which is particularly problematic for the study of rainfall in the winter months due to the increased likelihood of snow. As a result a number of sites were used as a comparison, the one chosen for presentation in the report is ‘Valley’.

5.5.2. Valley

Valley has been chosen because of the geographical and climatological contrast to Great Dun Fell. It is situated at an elevation of 10 metres in a coastal region of Wales which is exposed but not subject to the same magnitude and frequency of strong winds. Furthermore, the long record of nearly 50 years means that climate analyses are more possible.

Figure 25 shows the annual comparison of measured and corrected precipitation between June and September at Valley. Also included are annual averages of wind speed and temperature. Linear lines of regression are fitted to the data.

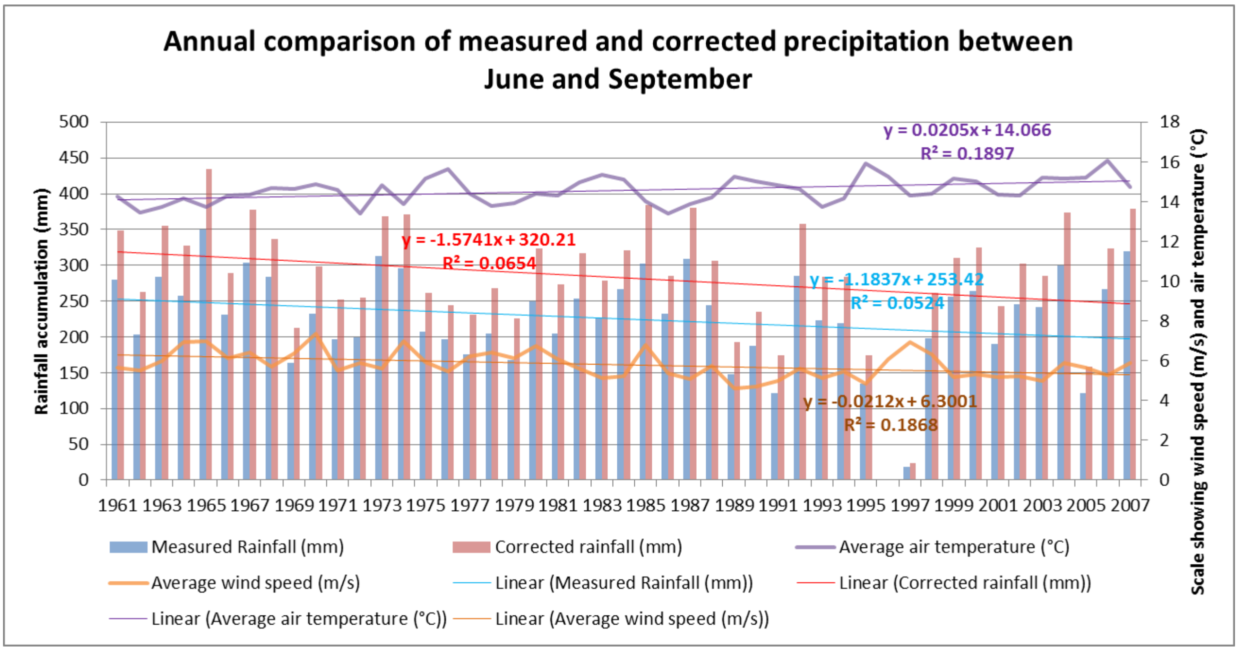


Figure 25: Comparison of measured and corrected precipitation between June and September at Valley, with linear regression equations fitted to the data

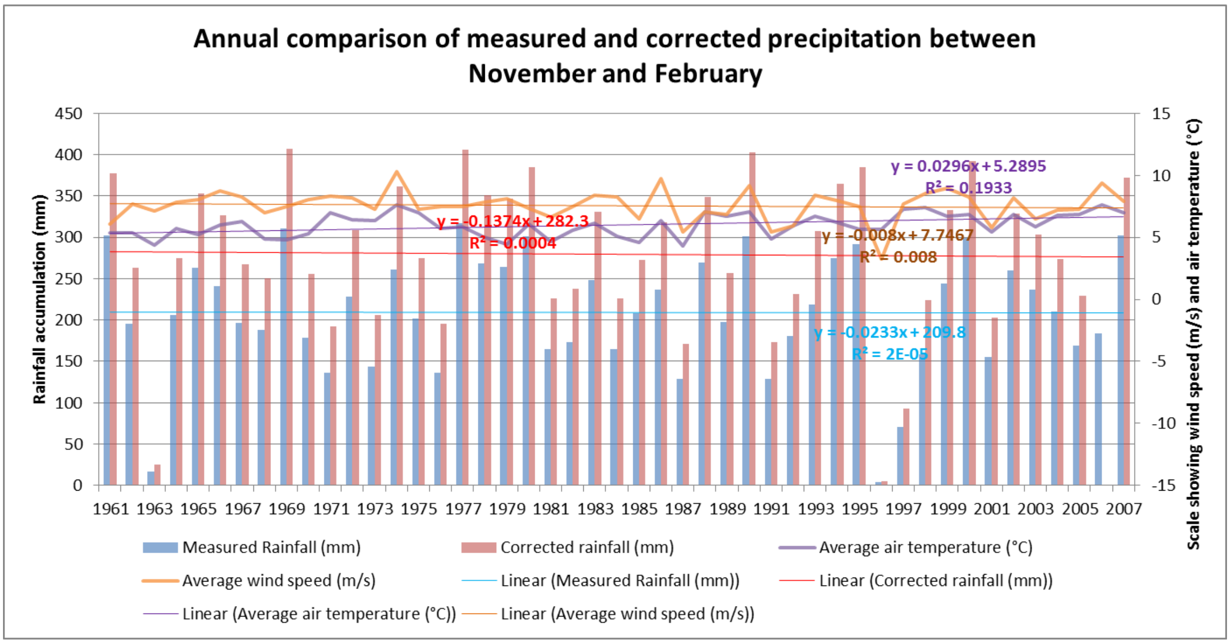


Figure 26: Comparison of measured and corrected precipitation between November and February at Valley, with linear regression equations fitted to the data

6. DISCUSSION

This section aims to bring together the three strands of evidence that have been studied; knowledge gained from literature, the high-resolution sub-hourly analysis from Gais Gill and Newton Rigg, and long-term daily resolution analysis. The aim is to discuss the findings and present a compelling argument for the UK to review their current operating procedure as regards precipitation measurement and correction. The argument is built sequentially through a series of sub-chapters which start with detailed analysis of results and culminate in a review of the implications of the findings.

6.1. Critical review of new types of instrumentation

The value of developing new instrumentation to measure precipitation directly is particularly compelling for a number of reasons. Strangeways (2010) maintains that in situ direct measurements of precipitation will remain the most important, and Habib et al. (2010) argues that despite the advances in remote sensing, rain gauge measurements continue to be the main basis for numerous research and operational applications. Agricultural purposes, water-resource monitoring, calibration, and assessment of remotely sensed rainfall estimates all require quantitative data about the surface rainfall amounts which are usually obtained by simple rain gauge measurements.

There is scope to develop instrumentation which is robust, low-maintenance, cost-effective and dynamic. The WXT 520 weather transmitter is the start of a new generation of instruments which have the ability to improve the accuracy of precipitation measurements in the future. However, the current effectiveness of these instruments is unclear. From the literature there was little evidence of thorough testing and calibration of the acoustic/ impact disdrometer component of the weather transmitter which is used to measure precipitation.

The statistical analysis carried out on the results from Gais Gill returned a ‘P’ value of 0.42, demonstrating that there is a significant difference between the measurements recorded by the impact disdrometer and those recorded by the more conventional, trusted and widely used tipping bucket raingauge.

It is notable that whilst the ARG 100 TBR collected a greater amount of rainfall than the WXT520, the difference was relatively small, only 5 mm. It is also clear that under some conditions the impact disdrometer performs better than the TBR. Due to the lack of availability of any longer comparative datasets it is not possible to test the significance of this, or statistically quantify and explain the reasons. However, with the new installation at Newton Rigg there will be a year’s worth of data by the summer of 2013 which has the capability of comparing fully the performances of three TBRs against two WXT 520s installed at different heights.

It will take many years of calibration, refinement and testing to convince hydrologists, climatologists and meteorological experts that impact disdrometers are more suited to recording rainfall accumulation than conventional raingauges, and this may not happen at all. However, these instruments have another purpose which has the potential to make them indispensable in future hydrological network installations. If the science of hydrology is to take seriously the need for accurate rainfall measurements, recording the microphysical structure of rain in the form of rainfall intensity and drop size distribution is essential. These parameters cannot be obtained from conventional TBRs but can be recorded by impact disdrometers, they are essential components of the most high-resolution and therefore advanced error correction procedures, such as the Michelson (2004b) DCM.

6.2. Critical comparison of tipping bucket rain gauges

The tipping bucket rain gauge is by far the most common type of rainfall measuring instrument that is used by both research and operational organisations (Habib et al., 2010). Due to their robustness, dynamism and cost-effectiveness this does not seem likely to change in the near future. However, within this framework there is considerable scope to refine the design to make it as aerodynamic as possible. The results from Newton Rigg conclusively show that the SBS collects more rainfall than the Casella Cel, and is therefore the better gauge. Whilst there is a large amount of scatter in the graphical presentation of these results, it can be statistically demonstrated that there is a very small but highly significant relationship between the difference in gauge catch, and the wind speed and rainfall intensity.

During the 15-16 months recording period of the Newton Rigg dataset the SBS recorded 12.52% more rainfall than the Casella Cel. It will be possible by the summer of 2013 to carry out a further comparison between these two gauges and another similar aerodynamically designed gauge as a result of the new installation and guaranteed frequent maintenance at the Newton Rigg site. This will yield a complete year of data, the results of which should verify the accuracy of the findings of this project.

The current aerodynamic designs of the TBRs such as the SBS or the ARG 100 are not necessarily the most effective at minimising distortion caused to the surrounding wind field. Chang and Flannery (2001) designed proposed a design to further reduce the magnitude of wind induced undercatch.

Chang and Flannery (1998) correctly state that the presence of the gauge distorts the surrounding wind field, however they attribute the resultant undercatch to water particles falling into the gauge at inclined angles, as shown in Figure 27 below. Whilst this is undoubtedly part of the problem, most scientists agree that it is the acceleration of wind speed above the gauge which carries rain particles over the orifice which is the main cause of undercatch (Habib et al., 1999; Sevruk, 2006).

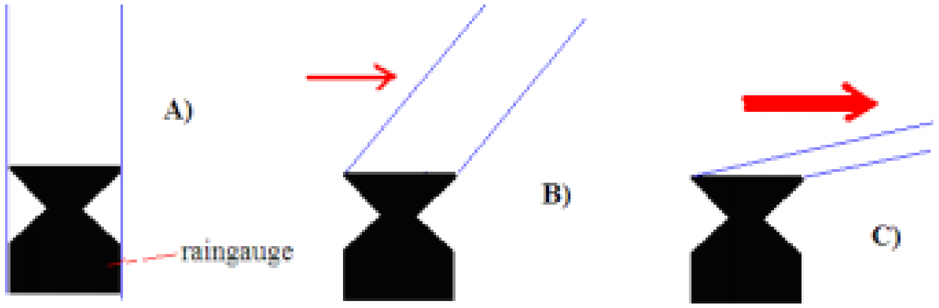


Figure 27: The effect of wind speed on the angle of inclination at which rain is caught by a gauge (Wilkinson, 2009)

As a result, Chang and Flannery (1998) developed a set of equations based on using the size of raindrops, their terminal velocity and the angle of inclination at which they fall to determine "true" precipitation. From their experiments this correction model improved the deficiency on average from -11% to -6%. They attribute the remaining deficiencies to "inaccuracy of wind speed, non-random error, or other unknown errors" (Chang and Flannery, 1998). Whilst their understanding of the issue is fundamentally incomplete, it provoked the development of the extremely interesting design of a semi-spherical or spherical gauge to try to mitigate undercatch as shown in Figure 28 below.

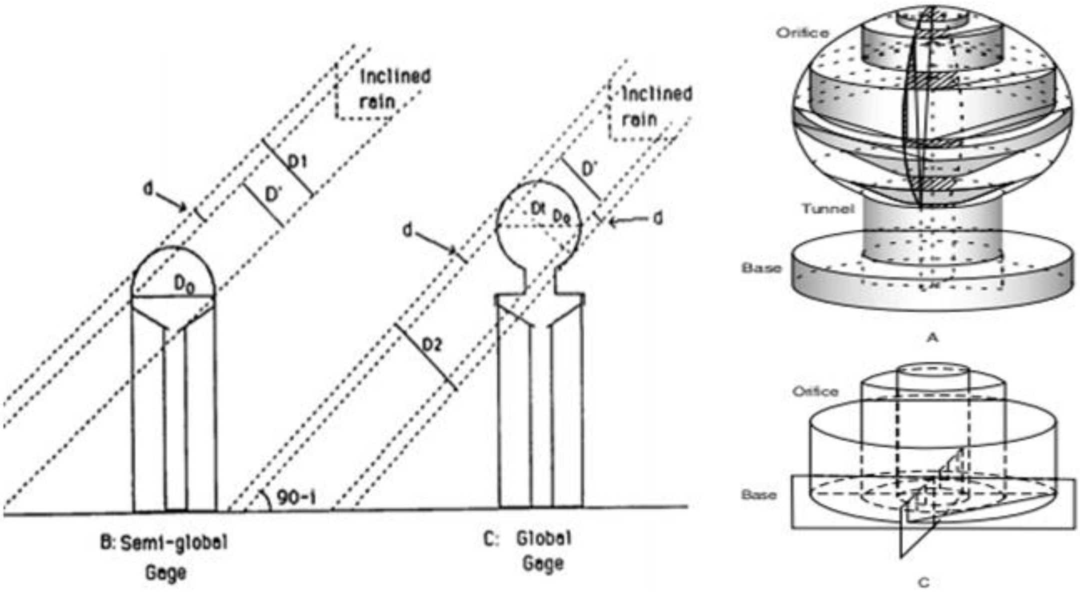


Figure 28: (Left) Difference in the effect of rainfall inclination angle on gauge catch for a semi-spherical and spherical gauge, and (right) the physical structure of the spherical gauge (Chang and Flannery, 2001; Chang and Harrison, 2005)

The spherical orifices are designed to catch rain with an effective diameter always equal to the actual diameter regardless of wind speed and direction, as shown in Figure 28 (Chang and Flannery, 2001). Further testing of this design produced results displaying that spherical gauges recorded on average 6-9% more than the US standard gauge and 3-4% less than a pit gauge (Chang and Harrison, 2005). Perhaps a more interesting result was that the catch of a spherical gauge is not significantly affected by gauge height above the ground, which is something that badly affects standard gauges and TBRs due to greater wind speeds at higher elevations. Jevons (1862) decisively shows this in his famous pioneering experiment noting the drastic difference in catch between a raingauge on top of a church and one set 100 metres away on the ground. The other notable quality of the spherical gauge was that the improvements were most significant for larger storms and for winds at higher speeds, which would make a great difference at a site like Great Dun Fell.

The difference in catch which would have resulted between an aerodynamically funnel-shaped TBR and the spherical gauge is unclear because it was only tested against the US standard gauge. It is assumed that the spherical gauge would catch more than the SBS or ARG 100 but this cannot be verified and besides, it would still need to be corrected to find the "true" precipitation. The most significant merits of the spherical gauge are its capacity to not be significantly affected by gauge installation height and perform better in high wind speeds.

For a particular application, if it is not possible or viable to apply a high resolution correction model or a pit gauge then the next best option is a robust, cost effective and low maintenance rain gauge which is dynamic and can perform well in large storm events with high wind speeds or low-intensity-high-wind events. Due to its unique design the spherical gauge appears to theoretically offer the best method of achieving this. However, more testing would be advisable before widespread adoption of this type of gauge. Perhaps it would be possible to acquire a spherical gauge which could be added to the enclosure at Newton Rigg.

6.3. Precipitation correction procedures

A number of different correction procedures were chosen to apply to the datasets used in this study. Each model of correction has its own unique set of advantages and limitations which make it applicable in a specific spatiotemporal context.

Correction formulae are generally based on the WMO field intercomparison methods or numerical simulation of wind tunnel experiments. They are only valid for certain timescales. Some are suitable for sub-hourly and hourly measurements (Michelson, 2004b) while others are applicable for longer timescales (Sevruk and Hamon, 1984). All types of models rely on the quality and quantity of input data. Field intercomparison methods invariably require a long period of measurement to establish and perform the correction procedure on a wide range of temporal scales varying from minutes to months, and are very costly (Habib et al., 1999). Simulation computations have many advantages, once the methodology is developed correction procedures for any type of gauge and any range of variables and very small time intervals can be made quickly (Sevruk, 2006).

6.3.1. Bias correction of precipitation climatologies using historical records

Retrospective bias corrections have been applied to a number of national and global climatologies. The procedures make use of existing historically archived national datasets of precipitation, wind speed and other climatic variables usually recorded on a daily time resolution. The correction models are usually derived from the WMO intercomparisons but are adapted to suit the operational differences between the recording of meteorological variables in different countries. For example, a bias-correction procedure applied to China's network of gauges needed to be adapted to account for wind speed readings which were recorded at a standard height of 10 metres above the Chinese standard precipitation gauge (CSPG), as well as being calibrated for the gauge itself (Ye et al., 2004). This study concluded that all 710 stations were susceptible to wind induced measurement errors, corresponding to between 6 and 62% increases for individual gauges and an overall mean increase of 19% in gauge measured yearly total precipitation over China (Ye et al., 2004). Another study involving the Tretyakov gauge over a 20 year period in Mongolia suggests that annual precipitation should be 17 to 42% higher after bias-correction procedures are applied (Zhang et al., 2004). A regional bias-corrected precipitation climatology is presented in Yang and Ohata (2001) for Siberia, concluding that the 61 climate stations annually underestimated precipitation by between 10 and 65%. Sugiura et al. (2006) carried out a study on the characteristics of five standard precipitation gauges in high-winds in Alaska, again discovering the tendency of national standard gauges to undercatch significantly. It must be noted that in many of these studies snowfalls are more than likely the main reason for the largest catch deficiencies and as a result all studies concluded that corrections were larger in winter than in summer. Yang et al. (2005) produced a study that corrected daily precipitation measurements over "the northern regions", which applied a consistent daily bias correction procedure to 4802 stations north of 45°N. The study looked at 30 years of precipitation data and discovered that the corrections generally enhance monthly precipitation trends by 5 – 20%.

The Sevruk (2006) correction model was applied for the months of June through to August because these months had complete or near complete records where air temperatures were above 2°C and therefore precipitation fell as rain. The average monthly modelled undercatch for June, July and August was 29.8%, 26.5% and 25.0% respectively. Compared with the literature these results do not appear to be particularly high. However, it must be remembered that these are for summer months where only rainfall is measured. In this context, an average summer monthly undercatch of between 25 – 30% can be seen as uncommonly high. It would be easier to have more confidence in the model results if it had been empirically calibrated for high wind speeds by field intercomparison or numerical simulation. The extrapolation required to develop the correction factor for high wind speeds weakens the confidence in the model results because it is possible that it is overestimating undercatch by an unknown amount.

6.3.2. New high resolution correction procedures

Correction procedures which are based on high resolution input variables produce results which have a greater level of confidence than the daily and monthly based corrections used for historical records. Their main issue is with the availability of the input data. There have not been many correction procedures of this nature developed due to the relatively new innovation of high resolution sub-hourly measurements. The quantity of wind-induced undercatch in the literature according to this model varies hugely and is not only dependent on wind speed but also the drop size distribution and rainfall intensity. For instance in wind speeds of 20 metres per second and temperatures above 5°C the DCM assumes a catch of 50%. It is possible to have a much greater level of confidence in the results of the DCM compared to the long-term bias corrections. The limitations of this model when it was applied to the datasets of Gais Gill and Newton Rigg are mainly concerned with the quality of input measurements and the unquantifiable error which using a different gauge causes.

The monthly undercatch for rainfall at Gais Gill according to the Michelson (2004) DCM ranges from 10.7 to 17.0%. Lower values are recorded in the winter months of December and January 2010/2011, which is unusual as one would expect higher undercatch in the ‘windier’ winters. However it must be remembered that during December and January of that winter there was an unusually large amount of snowfalls, which is shown by the unusually low values of recorded precipitation above 2°C. As a result, the higher undercatch values of October, November, February and March are more significant. Comparing these values with literature shows that it is perfectly possible that true precipitation was in the order of 14-17% more than recorded precipitation. However, the fact that the dataset is so short prevents any meaningful conclusions from being drawn on the accuracy of projected undercatch, other than qualitative speculation.

Applying the DCM to the Newton Rigg dataset also yielded interesting results. There is a clear pattern of a higher correction factor being applied in the winter where wind speeds are higher and more precipitation falls. The results from this data agree well with literature. The average correction factor for the winter months at Newton Rigg was 17.05% compared to 6% for the summer months. Two notable anomalies occur, there is a relatively low undercatch for December 2010 of 11.9%, however this can be attributed to the very cold winter with a lot of snow. There is also a very high amount of undercatch of 23% in May 2011, but this can be attributed to the erroneously high wind speed which was collected that month due to quality control issues.

Overall it is easier to be more confident with the results of the DCM compared to the results of the long-term correction procedure applied at Great Dun Fell. This is due to the high resolution of input data which dramatically improves the accuracy of correction models.

6.3.3. Effect of temporal averaging on corrections

There is a clear difference between models applied for daily data and high resolution data. However, to form national and global climatologies long-term techniques using data of a daily resolution are necessary despite their limitations. This is because the corrected values are likely to be closer to the true precipitation than measured values. There is clearly a place for both in the science of hydrometeorology but the corrections are still developing so it is equally important to preserve original datasets in case of future improvements.

One problem which continually arises in the literature is the effect of the temporal averaging scale on the estimation of wind-induced error correction. Increasing the correction timescale leads to a significant overestimation of the wind induced error (Habib et al., 1999). For instance if measurements are corrected on a daily scale instead of an hourly scale the wind-induced error could be overestimated by a factor of about 2-3 times, and can get as high as 5 times of corrections are performed on a monthly scale (Habib et al., 1999).

The effect of the temporal averaging scale can be seen in the data from Gais Gill, where the measurements have been corrected at a sub-hourly resolution using the DCM, and separately corrected using a daily averaged scale. The difference in projected catch is displayed in Figure 29 and summarised in Table 9.

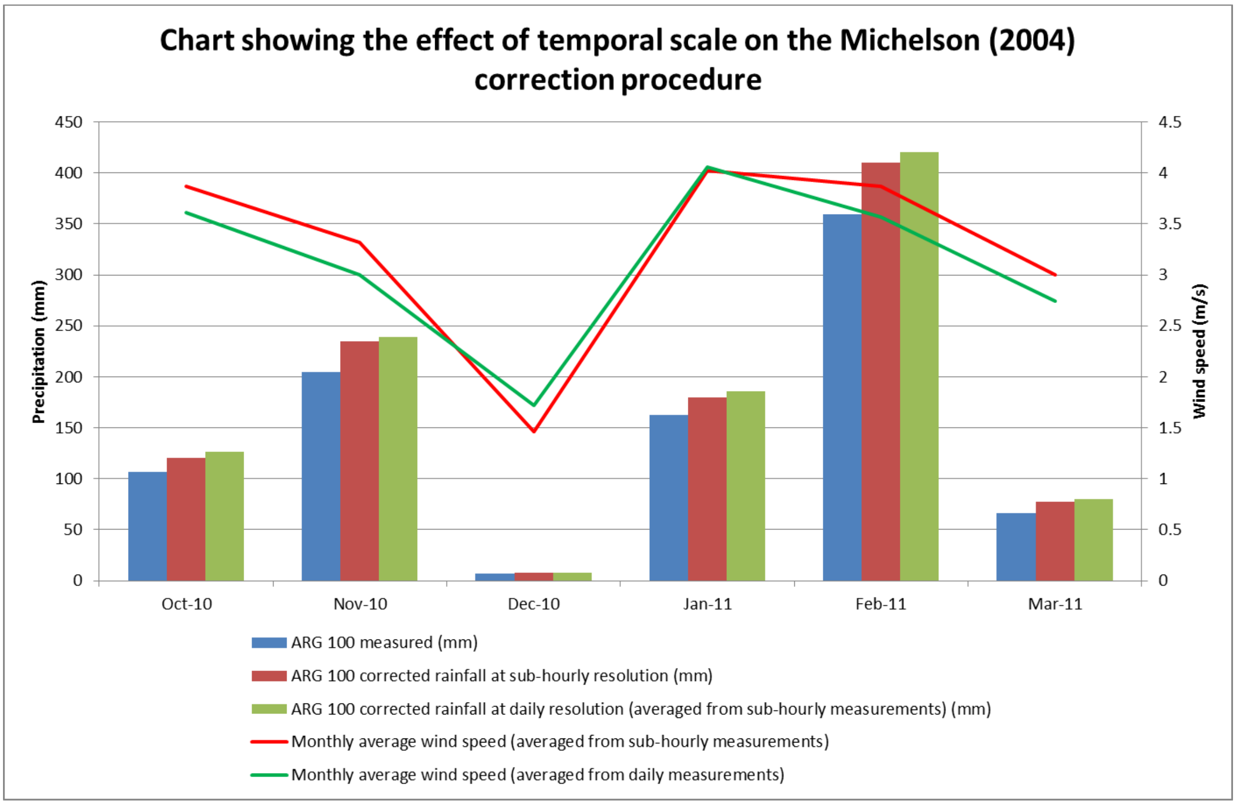


Figure 29: The effect of temporal averaging on the DCM at Gais Gill

Table 9: The monthly percentage increase in correction cause by temporal averaging

Year	Month	Increase in correction caused by temporal averaging (%)
2010	Oct	5.3
	Nov	1.5
	Dec	2.0
2011	Jan	3.3
	Feb	2.6
	Mar	3.3

Adjusting the temporal resolution of correction by averaging from sub-hourly to daily caused up to 5.3% of a difference, which would be magnified if the measurements were averaged again to the monthly scale. This shows the vital need for the refinement of correction procedures in order to obtain reliable unbiased rainfall estimates (Habib et al., 1999).

High-resolution correction factors should be valued highly within hydrology and more efforts should be made to develop them. Providing a consistent and accurate assessment of the input to the UK's water resources is more important now due to water stresses than it ever has been in recent history. In a changing climate which is subject to more extreme rainfall events there is also a potential to apply these corrections in real-time, and therefore greatly improve the accuracy of flood forecasting models. Aside from the study conducted by Michelson (2004) there is a gap in scientific literature on this type of high resolution model. The new installation at Newton Rigg provides a unique opportunity for Newcastle University to be at the forefront of developing a new dynamic correction model applicable for several designs of TBR in the Eden catchment. The instruments installed now have the capacity to record the microphysical rain structure parameters needed for an accurate model. If funding can be obtained to install and maintain a pit gauge for a year, there would be a reference gauge of “true” precipitation on which the model could be calibrated.

6.4. Long term analysis: climatic changes?

Considering the wider implications of undercatch was an important feature in this project. It was hypothesized that the effects of undercatch could change or distort observed changes in precipitation. For example, increases in wind speeds over time could magnify the effect of undercatch leading to a recorded decrease in precipitation, where in reality this may not actually be happening. Or an increase in temperature could also have an effect on the rainfall regime of a particular place. For instance, if average winter temperatures are increasing this could have an effect on the amount of precipitation falling as snow or rain. Undercatch is much greater for snow than rain so an apparent increase in precipitation could be attributable to the change of form from snow to rain.

Great Dun Fell had 17 years of near complete record so it was used in a preliminary investigation into the effects of other meteorological variables on precipitation. Since this study is concerned with rainfall the summer months of June to September were used to ensure that there was no snow. Figure 24 shows that there is a weak negative trend in measured precipitation, which is slightly stronger when undercatch is factored in. The corrected precipitation values have a slightly larger ‘r’ squared value which shows that undercatch may be significant because there is a slightly more significant trend when it is factored in. Wind speeds seemingly decreased a small amount, but as with most meteorological readings there is a large amount of natural variability which is a possible reason for the very low ‘r’ squared value. The greatest confidence is in the upward trend of temperature which appears to be larger than natural variation. However with a dataset of only 17 years any of these apparent trends could also be attributable to a natural multi-decadal fluctuation. As a result, looking for a weather station with a longer record was a reasonable undertaking to attempt to investigate trends more thoroughly.

Valley was selected because it had one of the longest records out of all whole BADC database, just less than 50 years. Furthermore, it is a low elevation coastal region which means that snowfall would not be as prevalent here as somewhere inland or at a higher elevation like Great Dun Fell. This means that it is possible to measure winter trends as well as summer.

Figure 25 shows the summer analysis which demonstrates that there appears to be a greater amount of reduction in measured summer rainfall, which is what is expected from the literature. The ‘r’ squared value is higher and the correlation stronger for corrected precipitation which again shows the significance of undercatch. Wind speeds appear to be decreasing and air temperature appears to be increasing. Regarded in tandem with the literature it is probable that the increase in air temperature is greater than could be explained by natural variations. No significant work has yet been carried out to assess trends in wind speeds so it is difficult to confidently say that they are decreasing at this site. However, research on this issue is currently being undertaken by Newcastle University. It is possible that the apparent weak negative trend is due to natural variations. Another possibility is that when many of the Met Office weather stations were installed in the 1960s trees would have been cut short around them. Over the subsequent 50 years the trees could have grown sufficiently to create a sheltering effect which could indicate an apparent decrease in wind speed such as shown here.

The winter results for Valley are shown in Figure 26 and they indicate that there appear to be no particular trend in measured precipitation. However corrected precipitation shows a slightly greater gradient and ‘r’ squared value which could show significance of accounting for undercatch. Wind speed appears to shows a very weak decrease but this is not enough to overcome natural variability. Again air temperature is increasing, arguably by more than could be explained by natural variability.

With the quality and availability of data and the relatively short amount of time which could be dedicated to this project, no emphasis has been placed on trying to categorically prove apparent changes in measured precipitation can be explained by observed changes in temperature or wind speeds. However, it is a significant result if this study can cast some degree of doubt on the current understanding of the UK’s rainfall regimes due to the lack of consideration of the effects of wind-induced undercatch. The next section attempts to provide a case to make this point.

6.5. Spatial and temporal fluctuation in UK rainfall: a critical review

A multitude of studies have been conducted which study the climatology of the UK over the twentieth century. Mayes (1996) reported fluctuations over the British Isles between 1941 -1970 and 1961 – 1990, stating that there were rainfall increases in winter in North-western areas. Fowler and Kilsby (2002) use seven sites in Yorkshire and report significant decreases in summer precipitation, increases in winter precipitation and enhanced variability. They also suggest that the incidence of higher winter precipitation totals at western sites may be linked to the increase in the North Atlantic Oscillation (NAO). Burt and Ferranti (2012) examine the shift in the pattern of UK rainfall in the context of orographic enhancement. The only mention that Burt and Ferranti (2012) make of the issues of wind induced undercatch is, "given that tall gauges are more susceptible to loss of catch during strong winds it is fortunate that British gauges are not taller, even if there is a risk of splash". This appears to show a lack of understanding of how a gauge of any size distorts the surrounding wind field causing significant acceleration of wind above the gauge orifice which causes the loss of catch. Fowler and Kilsby (2007) note a projected increase by 20-30% of mean monthly rainfall in winter and up to a 50% reduction in summer months. Perry (2006) presents a comprehensive analysis of the UK climate which states that since 1961 there has been a 38.9% increase in winter precipitation in Northwest England and a 7% reduction in summer precipitation.

The argument being put forward is that whilst a range of studies have been conducted on the UK's climatology they appear not to have explicitly considered wind-induced undercatch. Neither have they considered the implications which changes in other climatic variables could have on this undercatch, and the resultant effect on precipitation regimes. Countries such as China, Russia and Canada have produced bias adjusted rainfall measurements whereas the UK continues to rely on recorded rainfall for climatological studies. Mayes (1996) states that the data for temporal analysis of regional rainfall were obtained from the UK Meteorological Office and does not mention anywhere that they have been corrected for wind-induced undercatch. The other aforementioned studies also do not expressly consider the issue of wind-induced undercatch as one of outstanding importance. Perhaps now that severe instances of flooding and drought are becoming more frequent in the UK there will be a move to improve the accuracy of rainfall measurements, but this has not yet risen to prominence.

7. CONCLUSIONS

Precipitation measurements recorded by rain gauges with their orifice above ground level are always deficient due to systematic errors. Wind-induced undercatch is invariably the greatest of these inaccuracies and is higher for snow than for rainfall. Procedures have been developed empirically to correct precipitation data which are based on a range of input variables. The accuracy of the correction model depends on the availability, accuracy and temporal resolution of these input variables. High-resolution sub-hourly measurements produce the most accurate correction models. Temporally averaging the scale of correction can cause up to 5 times an overestimation in undercatch so the models need to be robust, dynamic and adaptable. More work needs to be carried out to improve correction models because they are currently inadequate and not widely used in many hydrological, agricultural and water resource applications. Research into studies on UK climatologies demonstrated a lack of consideration given to undercatch, which may have significant implications on findings. The issue of undercatch and the resultant underestimation of the input to UK water resources should rise to greater prominence as water stresses become more severe due to climate change.

Tipping bucket rain gauges are the most common type of recording gauge. They will remain integral in many hydrological monitoring networks for the foreseeable future due to their low cost, low maintenance and perceived accuracy. Weather transmitters provide a compact and useful service in many hydrometeorological applications, particularly those which are not easily accessible. However, they are expensive and their ability to measure rainfall as well as TBRs is currently questionable. Despite this, if the development of high-resolution precipitation correction models becomes a priority in future for water resource estimation, real-time flood modelling or other applications, there is a great opportunity for the impact disdrometer component of the weather transmitter to be harnessed to measure microphysical rain structure parameters at a high-resolution. Therefore, the potential of these instruments is invaluable if they can be improved or better calibrated. The new installation at Newton Rigg which Newcastle University are running in partnership with EML has the potential to be the starting point for development of a high-resolution correction procedure for the Eden catchment.

Long-term analyses of historic data records have been carried out in a number of studies of the UK's climatology over the twentieth century. The effects of undercatch have not been accounted for and corrected accordingly. Scientists in many countries have published bias-corrected climatologies which account for errors in precipitation measurement yet the UK have produced no national representation of corrected precipitation records. There could be a number of reasons for this, for instance it may be explained by lack of necessity for an accurate quantification of water resources due to a plentiful supply of water, but with increased water scarcity particularly in the south-east this apparent complacency may rapidly change. Undercatch should also be considered in the context of a changing climate. The long-term analysis conducted in this study did not produce much in terms of significant climate trends, but it hopefully exposed a research gap in the current level of understanding of the implications of undercatch.

8. RECOMMENDATIONS

Parts of the high-resolution analysis in this study were restricted by the limited length of available data records. In some cases such as at Newton Rigg the data were subject to quality issues which meant that there were significant gaps and they were sometimes unreliable. Significant improvements in the integrity of the study could be made if records were longer and there were fewer data discontinuities.

The integrity of the long-term analysis could be improved by studying a larger number of sites to provide greater comparison. Climate analyses and the confident identification of trends would be augmented by a larger number of study sites. It may also be possible to adapt a different correction procedure which could produce results that do not rely on linear extrapolation, a significant weakness of the Sevruk (2006) model used.

Throughout the entirety of the study there was no focus on extreme events which are enormously important as they can produce widespread flooding. If the study were to be extended it would include consideration and analysis of these. Furthermore, snow was considered outside of the scope of the study due to difficulties in applying correction procedures. If the study were to be repeated methods should be developed to overcome these difficulties.

There is clear potential for the new weather transmitters to play an important role in hydrological networks in the future, but more comparisons need to be undertaken to test them against the conventional methods of precipitation collection. The record available at Gais Gill was much too short to produce any significant results. In addition, the potentialities of these instruments to measure drop size distribution and rainfall intensity should be fully investigated. The new installation at Newton Rigg has huge potential to form the basis of pioneering work, therefore Newcastle University should continue to work closely with EML on this project and continue to develop it. If possible, the dense network of instrumentation should be maintained beyond the yearlong agreement to provide a longer dataset for future studies. Furthermore, the best way to develop correction procedures and be extremely confident in their results would be to install a pit gauge at the site. This would be a significant undertaking but once installed it would not require any more maintenance than the other instruments at the site, therefore it should be seriously considered. If it were to be installed all the ingredients would be readily available to develop a local-scale correction factor which could be calibrated and eventually upscaled to represent the entire Eden catchment. This would be an extremely worthwhile achievement.

The overall “dream” accomplishment would be to develop correction procedures built into the software of raingauges that would automatically apply a correction procedure based on high-resolution input variables. There is a precedent for this reported in the most recent WMO field intercomparison, described in Lanza and Stagi (2009).

REFERENCES

Allerup, P. and Madsen, H. (1980) 'ACCURACY OF POINT PRECIPITATION MEASUREMENTS', *Nordic Hydrology,* 11, (2), pp. 57-70.

BADC (2012) *About the BADC*. Available at: http://badc.nerc.ac.uk/home/about.html (Accessed: July 2012).

Bathurst, J. C. (2012) Future of the CHASM Eden network, 17/05/2012.

Burt, S. (2010) 'British Rainfall 1860-1993', *Weather,* 65, (5), pp. 121-+.

Burt, T. P. and Ferranti, E. J. S. (2012) 'Changing patterns of heavy rainfall in upland areas: a case study from northern England', *International Journal of Climatology,* 32, (4), pp. 518-532.

Chang, M. and Flannery, L. A. (1998) 'EVALUATING THE ACCURACY OF RAINFALL CATCH BY THREE DIFFERENT GAGES1', *JAWRA Journal of the American Water Resources Association,* 34, (3), pp. 559-564.

Chang, M. and Flannery, L. A. (2001) 'Spherical gauges for improving the accuracy of rainfall measurements', *Hydrological Processes,* 15, pp. 643-654.

Chang, M. T. and Harrison, L. (2005) 'Field assessments on the accuracy of spherical gauges in rainfall measurements', *Hydrological Processes,* 19, pp. 403-412.

CO. (2008) *Learning Lessons from the 2007 Floods - An Independent Review by Sir Michael Pitt.* London: Cabinet Office

Dale, M., Davies, P. and Harrison, T. (2012) 'Review of recent advances in UK operational hydrometeorology', *Proceedings of ICE: Water Management,* 165, (2), pp. 55-64.

De Smedt, B., Mohymont, B. and Demaree, G. R. (2003) 'Grubbs revisited: a statistical technique to differentiate measurement methods of the degree of exposure of raingauges in a network', *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 48, (6), pp. 891-897.

Durkee, J. (2010) 'Precipitation Measurement and the Advancement Toward Global Observations', *Geography Compass,* 4, (8), pp. 956-978.

Ekstrom, M., Fowler, H. J., Kilsby, C. G. and Jones, P. D. (2005) 'New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies', *Journal of Hydrology,* 300, (1-4), pp. 234-251.

Fowler, H. J. and Kilsby, C. G. (2002) 'Precipitation and the North Atlantic Oscillation: A study of climatic variability in northern England', *International Journal of Climatology,* 22, (7), pp. 843-866.

Fowler, H. J. and Kilsby, C. G. (2003) 'Implications of changes in seasonal and annual extreme rainfall', *Geophysical Research Letters,* 30, (13).

Fowler, H. J. and Kilsby, C. G. (2007) 'Using regional climate model data to simulate historical and future river flows in northwest England', *Climatic Change,* 80, (3-4), pp. 337-367.

Goodison, B. E., Louie, P. Y. T. and Yang, D. (1998) *WMO Solid Precipitation Measurement Intercomparison: Final Report.* World Meteorological Organization.

Guo, J. C. Y., Urbonas, B. and Stewart, K. (2001) 'Rain catch under wind and vegetal cover effects', *Journal of Hydrologic Engineering,* 6, (1), pp. 29-33.

Habib, E., Krajewski, W. F., Nespor, V. and Kruger, A. (1999) 'Numerical simulation studies of rain gage data correction due to wind effect', *J. Geophys. Res.,* 104, (D16), pp. 19723-19733.

Habib, E., Lee, G., Kim, D. and Ciach, G. J. (2010) 'Ground-Based Direct Measurement', in Testik, F. Y. and Gebremichael, M.(eds) *Rainfall: State of the Science.* Vol. 191 Washington: Amer Geophysical Union, pp. 61-77.

Hannaford, J. and Marsh, T. J. (2008) 'High-flow and flood trends in a network of undisturbed catchments in the UK', *International Journal of Climatology,* 28, (10), pp. 1325-1338.

IPCC. (2007) *IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva, Switzerland:

Jevons, W. S. (1862) 'On the deficiency of rain in an elevated rain-gauge, as caused by wind', *Journal of the Franklin Institute,* 73, (5), pp. 332.

Kurtyka, J. C., Stout, G. E. and Buswell, A. M. (1953) *Precipitation measurements study : annual report, 15 February 1952 to 15 February 1953 : methods of measuring precipitation for use with the automatic weather station.* Urbana: Illinois State Water Survey.

Lanza, L. G. and Stagi, L. (2009) 'High resolution performance of catching type rain gauges from the laboratory phase of the WMO Field Intercomparison of Rain Intensity Gauges', *Atmospheric Research,* 94, (4), pp. 555-563.

Lanza, L. G. and Vuerich, E. (2009a) 'The WMO Field Intercomparison of Rain Intensity Gauges'.

Lanza, L. G. and Vuerich, E. (2009b) 'The WMO Field Intercomparison of Rain Intensity Gauges', *Atmospheric Research,* 94, (4), pp. 534-543.

Lanza, L. G. and Vuerich, E. (2012) 'Non-parametric analysis of one-minute rain intensity measurements from the WMO Field Intercomparison', *Atmospheric Research,* 103, pp. 52-59.

Larson, L. W. and Peck, E. L. (1974) 'ACCURACY OF PRECIPITATION MEASUREMENTS FOR HYDROLOGIC MODELING', *Water Resources Research,* 10, (4), pp. 857-863.

Legates, D. R. and DeLiberty, T. L. (1993) 'PRECIPITATION MEASUREMENT BIASES IN THE UNITED STATES', *Journal of the American Water Resources Association,* 29, (5), pp. 855.

Mayes, J. (1996) 'SPATIAL AND TEMPORAL FLUCTUATIONS OF MONTHLY RAIDFALL IN THE BRITISH ISLES AND VARIATIONS IN THE MID-LATITUDE WESTERLY CIRCULATION', *International Journal of Climatology,* 16, (5), pp. 585-596.

Michelson, D. B. (2004a) 'Systematic correction of precipitation gauge observations using analyzed meteorological variables', *Journal of Hydrology,* 290, (3-4), pp. 161-177.

Michelson, D. B. (2004b) 'Systematic correction of precipitation gauge observations using analyzed meteorological variables', *Journal of Hydrology,* 290, (3/4), pp. 161.

Molini, A., Lanza, L. G. and La Barbera, P. (2005) 'Improving the accuracy of tipping-bucket rain records using disaggregation techniques', *Atmospheric Research,* 77, (1–4), pp. 203-217.

Nespor, V. and Sevruk, B. (1999) 'Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation', *Journal of Atmospheric and Oceanic Technology,* 16, (4), pp. 450-464.

Nespor, V., Sevruk, B., Spiess, R. and Hertig, J. A. (1994) 'MODELING OF WIND-TUNNEL MEASUREMENTS OF PRECIPITATION GAUGES'.

O'Connell, P. E., Quinn, P. F., Bathurst, J. C., Parkin, G., Kilsby, C. G., Beven, K. J., Burt, T. P., Kirkby, M. J., Pickering, A., Robinson, M., Soulsby, C., Werrtitty, A. and Wilcock, D. (2007) *Catchment Hydrology and Sustainable Management (CHASM): an integrating methodological framework for prediction.*

Osborn, T. J. and Hulme, M. (2002) 'Evidence for trends in heavy rainfall events over the UK', *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences,* 360, (1796), pp. 1313-1325.

Perry, M. (2006) *A spatial analysis of trends in the UK climate since 1914 using gridded datasets.* Exeter: Met Office

Peterson, T. C., Easterling, D. R., Karl, T. R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Forland, E. J., Hanssen-Bauer, I., Alexandersson, H., Jones, P. and Parker, D. (1998) 'Homogeneity adjustments of in situ atmospheric climate data: A review', *International Journal of Climatology,* 18, (13), pp. 1493-1517.

Robinson, M. (2006) 'Precipitation Measurement: Gauge Deployment', in *Encyclopedia of Hydrological Sciences.* John Wiley & Sons, Ltd.

Rodda, J. C. and Dixon, H. (2012) 'Rainfall measurement revisited', *Weather,* 67, (5), pp. 131-136.

Rodda, J. C. and Smith, S. W. (1986) 'The significance of the systematic error in rainfall measurement for assessing wet deposition', *Atmospheric Environment (1967),* 20, (5), pp. 1059-1064.

Sevruk, B. (1996) 'Adjustment of tipping-bucket precipitation gauge measurements', *Atmospheric Research,* 42, (1–4), pp. 237-246.

Sevruk, B. (2006) 'Rainfall Measurement: Gauges', in *Encyclopedia of Hydrological Sciences.* John Wiley & Sons, Ltd.

Sevruk, B. and Hamon, W. R. (1984) *International comparison of national precipitation gauges with a reference pit gauge.* Geneva: WMO.

Sevruk, B. and Klemm, S. (1989) 'Catalogue of National Standard Precipitation Gauges', *International Workshop on Precipitation Meausurement.* St Moritz, WMO, pp.

Sevruk, B., Ondras, M. and Chvila, B. (2009) 'The WMO precipitation measurement intercomparisons', *Atmospheric Research,* 92, (3), pp. 376-380.

Sevruk, B. and Zahlavova, L. (1994) 'Classification-System of Precipitation Gauge Site Exposure - Evaluation and Application', *International Journal of Climatology,* 14, (6), pp. 681-689.

Snorrason, A. and Puupponen, M. (2009) *Integration of environmental monitoring networks.* WMO

Stephens, G. and Kummerow, C. (2007) 'The remote sensing of clouds and precipitation from space: a review', *Journal of the Atmospheric Sciences,* 64.

Strangeways, I. (2006) *Precipitation: Theory, Measurement and Distribution.*

Strangeways, I. (2010) 'A history of rain gauges', *Weather (00431656),* 65, (5), pp. 133.

Sugiura, K., Ohata, T. and Yang, D. Q. (2006) 'Catch characteristics of precipitation gauges in high-latitude regions with high winds', *Journal of Hydrometeorology,* 7, (5), pp. 984-994.

Vaisala. (2012) 'Vaisala Weather Transmitter WXT520 Access to Real Time Weather Data', in www.vaisala.com.

Wagner, A. (2010) *Literature Study on the Correction of Precipitation Measurements.* Forest Monitoring for the Future (FutMon)

Wilkinson, M. (2009) *A multiscale nested experiment for understanding and prediction of high rainfall and flood response spatial behaviour in the Eden Catchment, Cumbria, UK.* thesis. Newcastle University.

Great Britain. Parliament. (2008) *Guide to Meteorological Instruments and Methods of Observation* WMO.

Yang, D., Kane, D., Zhang, Z., Legates, D. and Goodison, B. (2005) 'Bias corrections of long-term (1973-2004) daily precipitation data over the northern regions', *Geophysical Research Letters,* 32, (19), pp. L19501.

Yang, D. Q., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T. and Hanson, C. L. (1998) 'Accuracy of NWS 8" standard nonrecording precipitation gauge: Results and application of WMO intercomparison', *Journal of Atmospheric and Oceanic Technology,* 15, (1), pp. 54-68.

Yang, D. Q. and Ohata, T. (2001) 'A bias-corrected Siberian regional precipitation climatology', *Journal of Hydrometeorology,* 2, (2), pp. 122-139.

Ye, B. S., Yang, D. Q., Ding, Y. J., Han, T. D. and Koike, T. (2004) 'A bias-corrected precipitation climatology for China', *Journal of Hydrometeorology,* 5, (6), pp. 1147-1160.

Zhang, Y. S., Ohata, T., Yang, D. Q. and Davaa, G. (2004) 'Bias correction of daily precipitation measurements for Mongolia', *Hydrological Processes,* 18, (16), pp. 2991-3005.