**Revision and extension of the composite Carlisle rainfall record, NW England: 1757-2012**

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**Abstract (300 words)**

A 256-year composite monthly rainfall record representative of the lowlands around Carlisle, northwest England is presented, providing the third longest instrumental record of rainfall available in the UK and expanding the sparse network of long homogenous rainfall series. This paper describes the construction of the rainfall record for the period 1757-2012 and presents analyses of long-term annual and seasonal variability, with a particular focus on wet/dry extremes. Three primary rainfall records from Carlisle underpin the reconstruction, with others selected based on length of record and proximity to the primary recording stations. Linear regression and adjustment factors were applied to create a homogenous continuous rainfall record, assessed by cross-comparison with other long-term UK rainfall records. Double-mass curve and Standard Normal Homogeneity tests using long records representative of Manchester and Appleby confirmed that the Carlisle record is homogenous, but includes a period of uncertainty during the period 1886-1911, which is within the recognised instrumental phase of recording. Analysis of the series shows long-term temporal rainfall variability, with seasonal rainfall totals showing a significant increase in winter rainfall. An increasing trend in annual rainfall was also identified but is not significant. Several previously documented notable extreme wet (e.g. winter 1834) and dry (e.g. summer 1995) seasons were identified, along with several additional seasons (e.g. winter 1764 and summer 1891) that can be considered as extreme that occurred during the more poorly-understood eighteenth and early nineteenth centuries; placing recent extremes within the context of long-term natural variability. At the decadal timescale seasonal rainfall totals are highly variable. The wettest season fluctuates between autumn and summer until the late twentieth century (1990s), when winter became wetter than any other season for the first time on record.

**Key words (8 words)**

Rainfall, construction, time series, long-term variability, Carlisle, northwest England

**Introduction**

Long instrumental observations and records of climate provide valuable information on how climatic variables, such as, temperature and precipitation have fluctuated over time (Pfister et al. 1999; Dobrovolný et al. 2010). Individual records derived from single meteorological stations are useful for small scale (Brázdil et al. 2008) local studies of change (Brázdil et al. 2012; Diodato et al. 2013), but also contribute to larger networks of records (Camuffo and Bertolin 2012), important for regional and global scale understanding of climate variation (Pauling et al. 2006). For example, long homogenised precipitation series have been used to assess changes in the intensity of precipitation and examine return periods of extreme rainfalls applied in flood risk (Little et al. 2008) and water resource management (Osborn et al. 2000; Pauling and Paeth 2007). Analyses of historical temperature records from stations around the world have provided a greater understanding of natural temperature variability and improved estimates of anthropogenic effects on global warming (Brázdil et al. 2005; Böhm et al. 2010).

This paper describes the revision of the monthly composite rainfall record for Carlisle, northwest England, and its extension to 2012. A long-term rainfall record for Carlisle was originally developed by Craddock (1976) which was an annually averaged series for 1757-1973. A monthly series was later constructed by Tabony (1980) for 1845-1976, and subsequently extended back to 1757 by Jones (1983). No detailed descriptions of the construction of the existing composite monthly rainfall series for Carlisle, nor the records themselves, have ever been published. In this study, historic rainfall data was retrieved from sources identified in previous work, along with contemporary station data for Carlisle, to develop a homogenous, fully digitised monthly rainfall series for Carlisle for 1757-2012. The consistency and representativeness of the monthly record is statistically tested through comparison with long-term rainfall series representative of other sites in northwest England (e.g. Manchester, 1786, Manley 1972), and with records from northeastern England (Durham Observatory, 1850, Burt and Horton 2007) and central England (Radcliffe Observatory Oxford, 1767, Craddock and Craddock 1977). Finally, analysis of long-term seasonal and annual rainfall variability is undertaken applying statistical analysis methods to determine long-term trends, with a particular focus on extreme wet and dry seasons/years.

**Historical instrumental observing and reconstructions of European climate**

Meteorological observing began in Europe in the early seventeenth century following the development of reliable measuring instruments such as, the thermometer and barometer (Kington 1997; Camuffo et al. 2013). The earliest measurements of temperature were made in northern Italy and contributed to the first international meteorological network known as the *Medici Network,* which was composed of eleven stations in Europe operating from 1654-1667 (Camuffo and Bertolin 2012). Pioneers of meteorology in Europe also made observations of the barometer from 1657 in Italy, 1665 in Paris and 1694 in the UK (Camuffo et al. 2010). The earliest precipitation measurements were made by Richard Towneley, Burnley, UK in 1677 and by the early eighteenth century regular instrumental observations of precipitation were being made across Europe, with at least ten sites recording precipitation across the UK by 1720 (Craddock 1976; Jones 2001).

Only a small number of continuous, long meteorological records have been constructed using the earliest measurements of climatic variables available in Europe. For example, the earliest temperature measurements made in the UK contribute to the Central England Temperature series (1659-present), one of the longest continuous series of temperature in the world (Manley 1974). Similarly, Demarée et al. (2002) developed a regional temperature series representative of central Belgium from 1767, and Dobrovolný et al. (2009) developed a regional temperature series from 1500 for Central European using historical documentary and long instrumental temperatures records. Camuffo et al. (2013) recently constructed a Western Mediterranean precipitation series from 1797 using the 14 longest instrumental series from six areas of the Western Mediterranean basin. Generating continuous meteorological time series capitalising on early observations is challenging, as early measurements commonly include inconsistencies relative to contemporary observations. Factors such as changes in: instrumentation, siting, observing practices, and units of measurement are common causes of inconsistencies in long-term meteorological series (Aguilar et al. 2003). Few sites where early observations were made have been in continuous operation for long periods of time. In the UK, with the exceptions of the Kew (London) and Radcliffe Observatories (Oxford) in southern England, many sites where the earliest (seventeenth and eighteenth century) observations of rainfall were made, ceased within a few decades of commencement. At some sites, records were later recommenced by new observers in nearby areas, enabling the subsequent development of homogenised composite rainfall series that incorporate the early observations.

**Existing long UK rainfall records**

Rainfall records several centuries long have been compiled for various sites across the UK using the earliest measurements of rainfall made by pioneering meteorological observers of the late seventeenth and early eighteenth centuries. The British Rainfall Organisation, initially run by George Symons later incorporated into the Meteorological Office in 1919, was fundamental in identifying the early observers and published their measurements in annual volumes of *Symons’s* *British Rainfall* from 1861 until 1899, after which volumes were entitled *British Rainfall* for the years 1900-1968. Volumes published during 1969-1986 were known as *Monthly and annual totals of rainfall* and those published between 1987-1991 known as *Rainfall* (Burt 2010). Many of the existing long rainfall records were constructed during the 1970s, beginning with studies of single station records e.g. Kew Observatory (1697-1970, Wales-Smith 1971) and the Radcliffe Observatory, Oxford (1767-1814, Craddock and Craddock 1977); and composite series representative of single areas e.g. Manchester (1765-1971, Manley 1972), and the East Midlands (1726-1975, Craddock and Wales-Smith 1977). Recognising the importance of inter-regional variability of rainfall, Craddock (1976) grouped all known long rainfall records and produced annual rainfall series representative of eleven regions across the UK, to generate the first catalogue of long-term rainfall records.

Interest in the compilation of long rainfall records has continued sporadically since the 1970s to present day, with the development of regional precipitation series (e.g. HadUKP, Wigley et al. 1984; Wigley and Jones 1987; Gregory et al. 1991; Jones and Conway 1997; Alexander and Jones 2001), additional single site reconstructions (e.g. Durham Observatory, 1850-present, Burt and Horton 2007; Burt 2009), and extensions of existing records (e.g. the Radcliffe Observatory monthly rainfall series extended back to 1757 and forward to the end of 2011 by Todd et al. 2013). Existing rainfall studies of northwest England include the 200 year index precipitation series for the Lake District area (Barker et al. 2004), Jones’s (1981) study of rainfall for two sites in the northern Pennines, and the two regional precipitation series for northwest England (HadNWEP, Alexander and Jones 2001; Simpson and Jones 2012).

**Study area, data and methods**

The City of Carlisle (approximately 30m above Ordnance Datum (a. O. D.)), northwest England, is situated in the Solway Firth – Vale of Eden lowlands, 20km north of the Lake District, just south of the English-Scottish border (shown by CA on Figure 1a). Carlisle has one of the longest continuous monthly records of rainfall for a single site in the UK (1860-1981), with daily observations from 1872. A number of additional, shorter-duration records are also available, offering a rare opportunity to construct a continuous record of rainfall from 1757 to present. A composite rainfall record for Carlisle was first made by Craddock (1976) who constructed an annual total series (1757-1973), along with ten others for regions across England. A composite monthly series was subsequently developed by Tabony (1845-1976) (1980), and extended by Jones (1983) back to 1757 (1757-1982). The series developed by Tabony and detailed description of its construction, were included in the appendices of Tabony (1980), which is now missing from the UK Meteorological Office archive (personal communication with UK Met office archive 5th June 2014); however a copy of the data series was obtained from Prof. P. Jones for the purpose of this study. The extended series (1757-1982) developed by Jones (1983) remains unpublished and unavailable at present (personal communication, 19th May 2014). Revision and extension of the composite rainfall record for this site is important for several reasons. First, recent rainfall totals can be contextualised in the full instrumental record period improving understanding of long-term temporal variability of rainfall at the site, which can contribute to larger scale studies of regional rainfall patterns. Second, inter-annual and seasonal rainfall variability determines the availability of water in rivers, reservoirs and groundwater stores and so an improved understanding of long-term rainfall variability in this region will be useful for water resource management. Third, the complete series is over 100 years longer than the majority of climate series currently used for examining climatic variability in the UK (most start in 1860) and therefore can be used to improve understanding of the natural variations of the climate of northern England.

**Rainfall measurements at Carlisle**

The earliest rainfall measurements recorded in Carlisle were undertaken by Dr Carlyle at Abbey Street (35m O.D.) from 1757-1783 with a gauge sited on a wall (Table 1) (Craddock 1976). Carlyle recorded monthly and annual rainfall totals for a period of 27 years resulting in the first continuous rainfall record for Carlisle. Early meteorological measurements in the UK were often published in the *Philosophical Transactions of the Royal Society* or the *Gentleman’s Magazine*, which were popular publications during the eighteenth and nineteenth centuries, and were subsequently copied and archived in the Meteorological Office’s decadal year books (Figure 2) (Craddock 1976). One of the earliest (surviving) original publications of Dr. Carlyle’s meteorological observations was made in the *Philosophical Transactions of the Royal Society* in collaboration with the then Bishop of Carlisle in 1768 (Bishop of Carlisle and Carlyle 1768). Unfortunately, measurements of rainfall were not included, only observations of pressure, temperature and humidity and a general description of the weather. Following the cessation of this series in 1783, there was a short gap in meteorological observing in Carlisle, with no records available until commencement of a record at Shaddongate (12m O.D.), less than 0.5 kilometres from Abbey Street, by Mr William Pitt, in 1801. Mr Pitt kept a meteorological journal for 24 years from 1801-1824, which included observations of rainfall, temperature, pressure, direction and force of the winds, and general appearance of the sky. His original journal became the possession of Dr Thomas Barnes, who submitted it to *The Royal Society of Edinburgh* accompanied by his own personal explanatory remarks and was published by the society in 1830 (Barnes 1830). Along with Pitt’s original tabular meteorological observations, Barnes describes the observer,

*“For many years Mr Pitt had no particular occupation, and meteorology was his hobby. He devoted a great portion of his time to astronomical and meteorological observations, took great delight in keeping his journals, and was scrupulously accurate…(he) was seldom absent from home; and whenever any unavoidable circumstance obliged him to go to a distance, he always appointed a confidential person to take the observations for him.”* (Barnes, 1830, p. 1, 2)

and his instruments,

*“The rain-gauge is a copper vessel, and consists of a funnel inserted into a tube, with a narrow communication, to prevent evaporation. The cylinder is four inches in diameter, and the area of the funnel is ten times that of the cylinder…The rain-gauge stands in an open situation upon the garden-wall, about twelve feet above the surrounding ground.”* (Barnes, 1830, p. 5)

Continuous uninterrupted measurement of rainfall in Carlisle began in 1845 extending to present, with observations made at Parhambeck Church (15m O.D., 1845-1862), Carlisle Cemetery (35m O.D. 1860-1981), where daily recording also commenced, and from Carlisle Willow Holmes Wks (12m O.D., 1942-present). A number of other short monthly records of rainfall are available for Carlisle e.g. Scaleby Hall, Cumberland (1871-1873) and some annual total records for earlier years reported in British Rainfall (Symons 1862) e.g. 1860-1861 totals recorded by Captain E. James, R. E. for the Carlisle Ordnance Survey Office, which are useful for verifying monthly and annual totals in the longer-duration records used to construct the composite series.

**Station selection**

Meteorological stations were chosen to represent Carlisle based on their longevity, continuity of recording and proximity to where the primary (oldest) records for Carlisle were made (Figure 1b and c). Monthly data for the oldest part of the record (1757-1871) was photographed from the UK Meteorological office’s decadalyear books and transcribed, since the original documents used to record this data are unavailable, the Meteorological Office’s archived copies are the best source of early data available. Copies of accounts and reports within the *Philosophical Transactions of the Royal Society* and the *Gentleman’s Magazine* were also examined, as they contained additional information (meta-data) on weather observations made in Carlisle. Data for the remaining part of the record (1872-2012) were extracted from the British Atmospheric Data Centre’s MIDAS Land Surface Station dataset (UK Met Office). Additionally, the Hadley Centre’s regional precipitation series for the northwest of England (1873-present) was extracted (HadNWEP). Three primary records were selected as the basis of the reconstruction located less than two kilometres apart: Dr Carlyle at Abbey Street (1757-1783); Mr Pitt at Shaddongate (1801-1824); and Carlisle Cemetery (1860-1981). A further seven rainfall series were identified and all of these, except Dumfries (approximately 50m O.D.) and Applegarth Manse (54m O.D), are within 20 kilometres of Carlisle and the primary records; providing the minimum number of different stations required to construct a continuous rainfall record for Carlisle (Table 1).

Of all the rainfall records identified, Wigton Cumberland, Dumfries, Carlisle Cemetery and Carlisle Willow Holmes wks all contained periods of missing data, which were filled using a variety of methods, chosen based on the length of missing data in each series and availability of data for the same period from alternative sources and neighbouring stations. There are five months of missing data (Aug-Dec) in 1826 at Wigton Cumberland, which were filled by interpolating values for the same months from previous years, since data from a neighbouring station for this year could not be identified within a reasonable distance to Wigton. No series exists in Carlisle for the period 1784-1791. As a result, annual totals in the Dumfries record were used to derive monthly values and bridge the 1784-1791 gap in the Carlisle record. Monthly totals were estimated by calculating the percent of annual total for each month based on all years with recorded monthly totals at Dumfries. Data for Carlisle cemetery is available in digital format from the BADC for 1872-1981, with additional data for 1860-1920 recorded in the UK Meteorological office decadal year books. The digital series contains periods of missing data during: 1891-1910; 1964; 1973; 1976 (Jan-Sep); and 1982 (Aug-Dec). The period 1891-1910 was filled using archived data for Carlisle Cemetery, since values for years either side of the 1891-1910 gap were approximately the same as in the digital series and data for the period is the same as that used in the Tabony (1980) composite series. Periods of missing data during the twentieth century were filled using linear regression analysis with Carlisle Willow Holmes wks and subsequently the regional HadNWEP series. The earliest part of the record for Carlisle Cemetery (1860-1871) was initially derived using the archive records for the station; however, subsequent visual inspection of the series identified that rainfall values for 1860-1869 were questionably low. Annual totals were compared with those recorded in British Rainfall (1862) for Carlisle and Tabony’s (1980) composite series (not shown here), which confirmed the archive Carlisle Cemetery data as uncharacteristically low for the period,

*“ the rainfall in 1860 was considerably above the mean at most stations, the average excess over the mean of previous years being about 25 per cent. It was nearly 50 per cent in excess in… some parts of the Lake District, while at Manchester it was only 3 per cent… above it. There does not appear to be any station which had less than the usual fall” (*G. J. Symons, 1862)*.*

As a result, data for 1860-1869 was derived from Tabony’s composite series and data for 1870-1871 from the archive records for Carlisle Cemetery, since the values were exactly the same as those used in the Tabony (1980) series. Estimated values in the archive Carlisle Cemetery record during 1860-1869 (confirmed by metadata in the decadal year book rainfall sheets) are evidently too low for the period and were subject to adjustment by Tabony (1980), although it is not possible to confirm the exact method at present (appendix of Tabony 1980 missing from UK Met Office archive).

**Time series homogenization**

Given the number of individual stations required as sources of data for 1757-2012, a range of methods were applied to construct a homogenous composite rainfall record representative of Carlisle. Initially, the three primary stations (Abbey Street, Shaddongate, and Carlisle Cemetery) were compared by calculating monthly means and standard errors for a 24 year period; chosen based on the length of record available for Shaddongate (1801-1824). Comparable record lengths were selected from Abbey Street (1757-1780) and Carlisle Cemetery (1860-1883). Variation in mean rainfall for all months can be observed (Figure 3); however, for some months this is small (e.g. April, June, September, October and November) and calculation of two standard error bars indicates no significant difference in mean monthly rainfall between the three primary stations, increasing confidence in their inclusion in record extension for Carlisle.

Nearby stations were identified to bridge the gaps between the three primary rainfall records. These had available data for infilling and in the majority of cases provided an overlap period with other series. Linear regression and correlation were undertaken in three stages (A, B, and C) using the three primary stations as dependent variables and neighbouring stations as independent variables and using the longest available overlap period. The stations used, years of available data and those used in linear regression analysis are detailed in Figure 4 and Table 2.

To extend the earliest part of the record, linear regression analysis was performed using data from Abbey Street and Dumfries for the overlapping period: 1775-1783 (Table 2 and Figure 4). The regression equation was used to adjust data from Dumfries to ensure comparability with data observed at Abbey Street and to construct the first part (A)of the homogenous record: 1757-1791. Two regression equations were developed during the second stage of homogenisation (B)to adjust data from Wigton Aikbank and Wigton Cumberland to Shaddongate, the second primary rainfall series. This extended the record back to 1792 and forward to 1826. The third and final stage (C) of homogenisation began with regression between Carlisle Cemetery and Carlisle Parhambeck Church using an overlap period of 1860-1862. Data from the latter station were adjusted and used to extend the former record back to 1845. Next, the adjusted Carlisle Parhambeck Church record was used as the dependent variable in a regression analysis with the Applegarth Manse record. Values from Applegarth Manse were adjusted to further extend this part of the record back to 1827. To extend part C of the record to the end of 2012 linear regression analysis was undertaken using the records from Carlisle Cemetery and Carlisle Willow Holmes wks. Values from the latter station were adjusted and used to fill in missing values and extend the record. There were several periods of missing data in the Carlisle Willow Holmes Wks record totalling 26 months: 1964, 1973, Nov 1989, and Jan 2005. Unfortunately, it was not possible to fill in these using a record from a neighbouring station, as all other stations within a reasonable distance contained the same periods of missing data. Consequently, linear regression was performed using adjusted Carlisle Willow Holmes wks data as the dependent variable and the regional precipitation series for northwest England developed by the Hadley Centre (HadNWEP, Alexander and Jones, 2001). Adjusted values of the regional series were used to fill in the missing data and complete the construction of a continuous rainfall record for 1757-2012 (Figure 5, top).

Visual inspection of the plotted combined parts of the composite rainfall series revealed two periods of inhomogeneity, shown by three sharp discontinuities (A and C1, Figure 5, top). Annual average rainfall totals for three parts of the record: A, B, and C(section C divided into multiple 33 year period: C1, C2, C3, C4 and C5 because of greater length of this section), were calculated along with annual percentage differences. Comparison of parts of the record showed that the average percentage difference between section A with sections B and C (multiple) was 24%, and section C1 with C2, C3, C4 and C5 was 10% (Figure 6). Rainfall values comprising sections A and C1 were increased by 24% and 10%, respectively to correct for these inhomogeneities (Figure 5, bottom).

**Homogeneity testing**

The homogeneity of the constructed rainfall series for Carlisle was assessed by statistically cross-comparing with other independent long rainfall records that are considered homogenous from a number of sites within a similar precipitation region (northwest England), and from others distributed across England that have a long series (Aguilar et al. 2003; Burt 2009). Single site/area records were obtained for Appleby (1857-2012, shown by AP on Figure 1a) and Manchester (1786-1971, shown by MA on Figure 1a), along with the HadNWEP regional series (1873-2013) (Alexander and Jones 2001) and Barker’s (2004) index series (1788-2000) for the Lake District area as independent comparative long series from northwest England. In addition, the Durham Observatory record (1850-2012, shown by DU on Figure 1a) was obtained to make a comparison with a long-record available for a site east of the Pennine Hills, which lie between Durham and Carlisle and contribute to regional climate variations. Similarly, comparison was made with the Radcliffe Observatory rainfall record (1767-2011, shown by OX on Figure 1a), since this is a similar length to the Carlisle series and potentially most useful for assessing the entire constructed record.

Table 3 suggests that the Carlisle record presented here is most comparable to Manchester and Appleby in terms of total rainfall, mean and standard deviation for the 99-year common record period, although reported values for each calculation are lower. This is expected since annual average rainfall at Carlisle (calculated for the 1916-1950 period, since this is the period used to generate the rainfall series for Manchester by Manley, 1972) is 817mm compared to 930mm at Appleby and 900mm at Manchester. Large topographic and rainfall variability in this region results in a poor correlation with the regional series (HadNWEP and the Lake District index series); however, the Carlisle record is potentially useful in extending these back in time by applying statistical methods to determine the relationship between the series. The Carlisle record also does not compare well with either the Durham or Radcliffe Observatory records, which have almost identical rainfall totals (64233.68mm, 65475.12mm), means (54.07mm, 55.11mm) and standard deviations (31.56mm, 31.97mm) (Burt and Howden 2013). This finding supports the assertion that regions on the leeward side of areas of high elevation (in this case the north Pennine hills) show a rain-shadow effect, and that the rainfall signature of northeast England is more closely related to that of the (central) south and southeast of England than that of northwest England, as proposed by Fowler et al (2005) and Burt and Horton (2007). Consequently, the Manchester and Appleby records were used for further comparative analysis and homogeneity testing of the constructed Carlisle record; using Manchester to test the earliest part of the record (1786-1971) and Appleby the latter part (1857-2012). It should be noted that there are considerable distances between Carlisle and Manchester (~190Km) and Carlisle and Appleby (55Km). As such, there is the potential for differing climate systems to affect these sites which will be reflected in the rainfall series; however, these are the best available records to undertake further comparative analyses with the Carlisle record constructed here.

The double mass curve test (Craddock 1979) was applied, which directly compares cumulative rainfall totals between a test station (i.e. Carlisle) and a reference station (i.e. Manchester) to assess relative homogeneity. Changes in gradient in the curve indicate discontinuity in one of the two series, which may arise from natural or non-natural causes (e.g. changes in the local environment). The method is a widely used test of the relative homogeneity of climate time series, but no information on the timing of discontinuities, the magnitude of the change, or the attribution of the break to a particular series can be gained (Searcy and Hardison 1960; Craddock 1979; Alexandersson 1986; Camuffo et al. 2013). As a result, the Standard Normal Homogeneity Test (SNHT) of Alexandersson (1986) is used to provide an indication of the timing and magnitude of potential inhomogeneities in the series.

Annual total rainfall series for Carlisle and Manchester were generated for the common period 1786-1971. Annual rainfall totals for Carlisle significantly correlate with those for Manchester at the 95% significance level (r= 0.51, p= <0.0001). Annual total rainfall series were then generated for Carlisle and Appleby for the common period 1857-2012. Annual rainfall totals for Carlisle also significantly correlate with those for Appleby at the 95% level (r=0.78, p=<0.0001).

Double mass curves were plotted using cumulative annual rainfall series for Carlisle, Manchester and Appleby. Ratio (Qi) and test statistic (Tv) (Equations 1 and 7; Alexandersson 1986) series were generated for each record comparison using annual rainfall series as part of the SNHT (Figure 7A, B and C). The double mass curve for Carlisle and Manchester (1786-1971, Figure 7A) shows a linear increase from the origin, but contains two changes in slope. The Qi series, essentially the standardised difference between the two rainfall series, shows a rise during the 1880s. This coincides with a statistically significant breakpoint, determined (Tv>7.75; n=25; significance level 95%) by difference calculations for two contiguous 25 year windows moved at annual steps through the data series and using the mean difference in precipitation between the two stations. The peak in Tv of 29.4 is centred on 1886, the last year with the lower mean precipitation. The decline in Qi during the 1910s identifies a further statistically significant breakpoint (Tv= 27.5) in 1911. This analysis suggests that the Carlisle series is consistent with the Manchester series from 1786-1885 and after 1912-1971, but contains a period of inconsistency during 1886-1911. The double mass curve for Carlisle and Appleby (1857-2012, Figure 7B) also shows two changes in slope. A decline in Qi around 1910 and rise during the 1930s coincide with statistically significant breakpoints identified 1909 (Tv=20.2) and 1933 (Tv=21.3).

Analysis of the double mass curve and SNHT for Manchester and Appleby (1857-1971, Figure 7C) assesses the relative homogeneity of these reference series, and was undertaken since the detected breakpoints in comparisons with Carlisle occur at differing times. Three changes in slope occur in the double mass curve along with a gradual decline in the ratio series around 1890 and rise during the 1930s. Statistically significant breakpoints occur at 1891 (Tv=21.0), 1911 (Tv=19.6) and 1934 (Tv=16.8). The breakpoints 1933/34 are only detected in comparisons made with the Appleby rainfall series (Figure 7 B and C), and perhaps are a feature of this rainfall series. The 1886 and 1891 breakpoints are observed only in comparisons with Manchester (Figure 7 A and C), but it is difficult to attribute these to the Manchester series alone as they differ in the timing by four years. The 1909 and 1911 breakpoints are present in all comparisons (Figure 7 A, B and C).

Tests of the relative homogeneity of the Carlisle record constructed here have confirmed the homogeneity of the series for the earliest part of the record (1786-1885: Figure 7A); the period including the earliest instrumental observations of rainfall at Carlisle and the greatest number of individual records required to construct the continuous 256 year record. Breaks in the homogeneity of the series around 1886, 1891, 1909, 1911 and 1933/4 have been identified, with the latter breaks attributed to the Appleby series only. This suggests the Carlisle series during 1886-1911 is inconsistent with the reference series from both Manchester and Appleby. The 1890-1910 period in the Carlisle Cemetery record (Figure 4) was a period of missing data in the digitised series; however, archive data for the station was available and used to fill this gap. Analysis of years either side of this gap showed that the two records were almost exactly the same, and the Tabony (1980) series is also exactly the same as the archive Carlisle Cemetery record for the 1890-1910 period and multiple years either side. Decadal yearbooks (UK Meteorological Office) and the online digital repository of rainfall data for Carlisle (BADC) provided no evidence of a physical cause; such as a change in instrumentation, as an explanation for this detected inhomogeneity. This period coincides with the well-documented long-duration severe drought event of 1890-1910, identified as the period including the most sustained drought conditions in the instrumental record (Marsh et al. 2007). This extreme multi-decadal climate variation from normal conditions may also be a cause for the detected breakpoints and inconsistency. This coupled with higher levels of confidence associated with modern instrumental record, suggests that natural variations in rainfall between these sites may be showing as statistical inhomogeneities in the constructed rainfall series.

**Analysis of the Carlisle rainfall reconstruction**

Annual rainfall totals for 1757-2012 are shown in Figure 8. The long-term mean is 786.5mm with a standard deviation of 112.0mm. Table 4 lists the top ten wettest and driest individual years on record. The highest annual rainfall total was 1199.9mm recorded in 1903 and lowest was 546.2mm in 1855. The top ten wettest years shows that the last decade has witnessed two of the wettest years, but also that two of the wettest years were recorded during the three years 1900-1903, in the middle of the long drought of the c.1890-1910. The top ten driest years are relatively evenly distributed throughout the entire record, with a high ranking dry year observed in each of the four centuries represented, with two of the top ten dry extremes also occurring in the last decade and four since 1989. Over the entire record period there is a slight increasing trend in annual rainfall totals towards the present, however the correlation coefficient with time (r= 0.10) is low and the trend insignificant (p= 0.11, at 95% level).

Calculation of seasonal rainfall totals and their long-term means shows close agreement between summer (223.3 mm) and autumn (232.4 mm) totals and more of a distinction with winter (185.3 mm) and spring (145.5 mm), a finding concurrent with the analysis of rainfall at Durham (1850-2000), although reported totals for each season are higher here (Burt and Horton 2007). Statistical analysis (linear regression, correlation and significance testing at the 95% level) undertaken for each season for the full record identify winter as the only season with a significant increasing trend; correlation coefficient with time (r= 0.15) is low, but significant (p= 0.02). There is a slight positive correlation observed for spring (r= 0.09), but this is not a statistically significant trend (p=0.14). The correlation coefficients for summer and autumn rainfall are much lower than those observed for winter and spring rainfall (summer r= 0.02, p= 0.73; autumn r= 0.04, p= 0.48), showing no statistically significant trend.

At the decadal timescale, seasonal rainfall totals are highly variable, as shown by oscillations throughout the entire record (Figure 9). During the second half of the eighteenth century autumn is wetter than any other season. Throughout the nineteenth century the wettest season fluctuates between autumn and summer, with summer being the wettest season overall. At the turn of the twentieth century, autumn, summer and winter rainfall totals are similar. Autumn and summer continue to be the wettest seasons as the twentieth century progresses, with a decline in winter rainfall totals observed during 1930-1970. Winter becomes the wettest season for the first time on record in 1996. Spring is consistently the driest season, with rainfall totals similar to those observed in winter during: 1786, 1822, 1862, 1972, and 1996.

Several well documented wet and dry extreme winter and summer seasons and a number of UK flood and drought events are depicted in the ranked list of seasonal extremes (Table 5). Barker (2004) identified the winters of 1834 and 2000 as the wettest on record (1788-2000) using the central Lake District (CLD) index rainfall series. At Carlisle, the wettest winter occurred in 1764, followed by 1834, with winter 2000 ranked eleventh (1757-2012). The widespread flooding during 1947 (Murray 1993) and 2012 (Parry et al. 2013) are depicted in the top ten wettest seasons. Of the worst flood events at Carlisle identified by Macdonald (2006) only the summer flood of 1856 is related to an exceptional wet season, as flood generation is often related to heavy rainfall in the upland headwaters of the Pennines and Lake District areas of the river Eden, resulting in lowland flooding of Carlisle. All of the water resource drought events recognised by United Utilities, the water resource provider for northwest England, are identified in the top ten seasonal extremes: 1933/34, 1963, 1975/76, 1984 and 1995/96 (DWRMP 2013).

**Summary**

The UK has a long history of meteorological observation and recording, with the earliest instrumental observations of rainfall at Carlisle dating back to the mid-eighteenth century. The quality and quantity of rainfall series for Carlisle provide a rare opportunity to construct a continuous monthly rainfall record, capitalising on the earliest observations, which can be extended to the present day. The 256 year record constructed here is now fully digitised and represents the third longest rainfall series available for the UK, after the Pode Hole rainfall series (Spalding, southeast England) dating back to 1726 and the Kew Observatory record (London, southern England) from 1697, and is the longest record available for northern England.

A number of standard approaches for homogenising and testing the constructed record were applied to ensure the earliest observations were comparable with contemporary rainfall observations and that the record is consistent and reflects natural variations of the climate of northwest England. The composite record was primarily constructed applying linear regression analysis on periods of overlap between individual rainfall records. Visual inspection of the plotted rainfall series revealed two periods of inhomogeneity (parts A and C1) after linear regression was undertaken. Correction factors were determined based on annual percentage differences between the differing parts of the record and the inhomogenous sections were adjusted to produce a homogenous composite record (1757-2012).

The exact causes of these inhomogeneities cannot be determined because of the lack of available metadata accompanying many of the earliest observations. It is only possible to speculate that these are the result of differences in instrumentation, siting and/or observing practices that are common causes of sharp discontinuities in long climatic time-series (Aguilar et al. 2003). Unlike other existing rainfall reconstructions that derive adjustment factors based on station metadata, as undertaken by Knox-Shaw and Balk (1932) on the Radcliffe Observatory record (available from 1767), it was not possible to apply the approach here, since little information on the earliest instruments and observations can be found.

The relative homogeneity of the constructed series was assessed using long-duration reference series available from northwest England and two common homogeneity tests. Their application to assess the length of record constructed here from a region with high natural rainfall variability proved to be highly challenging. The Carlisle series was confirmed as homogenous overall, including the period of record incorporating the earliest observations. A period of uncertainty was identified during 1886-1911, coinciding with a sustained well documented multi-decadal drought event in the region, and is a period of recording with no accompanying metadata. Breaks in the homogeneity of all rainfall series comparisons were detected during the twentieth century, suggesting that natural rainfall variability is perhaps being detected as inhomogeneities in rainfall series from this region.

Analysis of the entire rainfall record identified a significant increasing trend in winter rainfall and an increasing trend in annual rainfall totals, but this was shown not to be significant; with no significant trends observed for the other seasons. The increasing trend in winter rainfall is in agreement with trends identified in other long-term records available for the UK (e.g. Durham Observatory, Burt and Horton 2007) and is consistent with broader patterns of observed rainfall for the whole of the UK. For example, Jones and Conway (1997) found that the UK demonstrated trends towards wetter winters and drier summers based on analysis of the England and Wales (EWP) precipitation series for 1840-1995. Further analysis of this gridded dataset for 1961-2006 by Jenkins et al. (2008) also identified an increasing trend in winter rainfall for the western UK, including the north of England, Scotland and Wales, with a slight decreasing trend in summer rainfall totals for the same areas. The increasing trend in winter rainfall appears to be a widespread and unequivocal observed change in the pattern of rainfall regardless of length of record used for analysis; however, the signal for summer rainfall trends is much more inconsistent, with studies reporting both significant decreasing and increasing trends, while no significant trend was found in the Carlisle series. Trends in heavy rainfall events and their contribution to seasonal and annual totals using daily series has been studied for the whole of the UK by Osborn et al.(2002), Osborn and Hulme (2002), and Maraun et al.(2008) for recent decades (1961-1990); and recently for upland northern England by Burt and Ferranti (2012) over a longer timescale (1850-2000). These studies identify a clear signal towards more frequent heavy falls of rain in winter and less frequent heavy falls in summer contributing to total rainfall amounts over recent decades. Analysis of the daily Durham rainfall record (1850-2000) by Burt and Horton (2007) found that a reduction in heavy rainfalls during summer was the greatest contribution to the observed increasing winter and decreasing summer trends in rainfall totals. Examination of daily rainfall records from 1872 for Carlisle would be beneficial, permitting further investigation of seasonal and annual rainfall trends, but is beyond the scope of this study.

Over the 256-year time period presented, the record exhibits several well-known notable extreme wet (e.g. winter 1834) and dry (e.g. summer 1995) seasons as identified in other hydrometeorological time series (Cole and Marsh 2006; Barker 2004). Multiple additional seasonal extremes (e.g. winter 1764 and summer 1891) have been identified here that occurred during the more poorly-understood eighteenth and nineteenth centuries in comparison to extreme events of the twentieth century; placing recent extremes within the context of long-term natural variability. This is particularly important for deriving robust return period estimates of extreme events that are required for water resources planning in the UK, commonly undertaken using hydrometeorological time series from the early twentieth century onwards, and improving understanding of observed and predicted rainfall trends identified for the UK. Only a handful of rainfall records exist that span the entire period of instrumental recording in the UK. These records are highly valuable, offering rare opportunities to examine long-term observed natural rainfall variability at individual sites, which when viewed collectively as a network, present opportunities to examine regional and national rainfall variability.

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**Tables**

Table 1. Sources of rainfall data used in the construction of the composite Carlisle record. The three primary records used as the basis for the reconstruction are highlighted in bold, with approximated elevations given in italics *N.B.* The first initial of the earliest observer is reported as Dr. J. Carlyle by Craddock (1976) and Jones (1983) and as Dr. G. Carlyle by the Bishop of Carlyle (1768)

Table 2. Details of linear regression analyses performed for each stage (A, B, and C)including correction factors and strength of statistical relationship between stations

Table 3. Analysis of monthly rainfall for Carlisle and other long rainfall records available for northwest, northeast and southern England calculated on the 1873-1971 period common to all records

Table 4. Top 10 wettest and driest years at Carlisle during 1757-2012

Table 5. Top 10 wettest and driest seasons during 1757-2012

**Figures**

Figure 1. a) Location of sites and rainfall records used ; b) Locations of meteorological stations used to construct the composite rainfall record for Carlisle, with approximate locations of where the Wigton and Dumfries meteorological observations were made shown by a star; and c) Locations of meteorological stations in Carlisle

Figure 2. An example of a meteorological journal made in Carlisle, Cumberland (former county name of Cumbria), published in Gentleman’s Magazine for January 1756 (top) and a loose leaf page of Dr Carlyle’s rainfall measurements archived in the Meteorological Office’s decadal yearbooks (bottom). Source: UK Meteorological Office Archive, Exeter

Figure 3. Monthly mean rainfall (Jan-Dec) for 24 years with two standard error bars calculated for the three primary meteorological stations

Figure 4. Sources of rainfall data used in the construction of the composite rainfall record for Carlisle for 1757-2012. Rectangular boxes show all years of available data, with shaded areas showing actual years used to construct the rainfall record. Primary station names highlighted in bold and stages of linear regression show by A, B and C shading

Figure 5. Composite annual rainfall record showing inhomogenous sections A andC1 before 24% and 10% adjustment factors applied (top) and after (bottom)

Figure 6. Annual average rainfall totals calculated using 33 years of data from each part of the composite Carlisle rainfall record: A)1757-1789, B) 1792-1824, C1) 1827-1859, C2) 1862-1894, C3) 1897-1929, C4) 1932-1964, and C5) 1967-1999. Top after linear regression, bottom after 24% adjustment to A and 10% adjustment to C1

Figure 7. Test statistic (Tv) series (Top) and ratio Qi series (middle) performed following the SNHT approach of Alexandersson (1986). Chosen critical threshold level for Tv is 7.75 at T95, the 95 percent level, for n=25. Double mass curve of cumulative annual rainfall totals (bottom) for A) Carlisle and Manchester, 1786-1971; B) Carlisle and Appleby, 1857-2012; and C) Manchester and Appleby, 1857-1971

Figure 8. Annual rainfall totals for Carlisle: 1757-2012 with 10 year moving average and linear trend line (r= 0.10, p=0.11)

Figure 9. Seasonal rainfall totals at Carlisle shown by ten year moving averages

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