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An analysis of rainfall across the British Isles in the 1870s

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Abstract

Monthly records for the period 1871-1970 from 91 stations across the British Isles are used to place very high rainfall totals during the 1870s, 1872 and 1876-77 in particular, in context. Comparisons are drawn with 2012 and the winter of 2013-14, both of which were exceptionally wet in parts of the British Isles. Traditional Lamb Weather Type count and objective measures of atmospheric circulation obtained from reanalysis of surface pressure charts are used to classify the weather conditions under which these very high rainfall totals were generated. The normally wettest locations in the British Isles, i.e. the uplands in the north and west, were not unusually wet in the 1870s whereas locations with extremely high rainfall totals (relative to mean annual rainfall) tended to be further south and east in the lowlands. These exceptionally high totals were associated with a high frequency of cyclonic weather types and high scores for atmospheric vorticity; at the same time, the frequency of anticyclonic weather and of westerly winds tended to be very low. The winter of 2013-14, remarkably wet in southern England, was somewhat different in that the frequency of westerly air flow and resultant flow were both very high but so too were vorticity and the frequency of cyclonic weather types; the year 2012 experienced similar atmospheric conditions. The results confirm the importance of cyclonic weather for large rainfall totals across much of the British Isles; strong westerly winds seem only to favour the uplands and north-west coastal locations.

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1. Introduction

There is now unequivocal evidence of global warming over the last two centuries, usually reflected at regional scales (IPCC, 2013). According to the Clausius–Clapeyron relation, increased air temperatures will lead to increased evaporation and higher water vapour content in the atmosphere; precipitation must inevitably increase too. Averaged over mid-latitude land areas of the Northern Hemisphere, there is a high level of confidence that precipitation has increased since 1951 (Hartmann et al., 2013). Most climate models project increases in both rainfall frequency and intensity at higher latitudes in the Northern Hemisphere, including northern Europe (e.g. Meehl et al., 2007; Hartmann et al., 2013). Research has found that both flood magnitude and frequency in the UK may have increased over the last five decades. (Pattison and Lane, 2011). There has been a tendency in the UK, particularly in the 1990s, for heavy falls of rain to increase in winter and decrease in summer, especially in the uplands (Osborn et al., 2000; Malby et al., 2007; Maraun et al., 2008; Burt and Ferranti, 2012). Although drier summers are projected in the future, driven by substantial warming of the North Atlantic, (Sutton and Dong, 2012), the UK can still experience wet ones like 2007 and 2012 and heavy falls remain very likely even in dry summers. It is therefore important to understand precipitation variation in all seasons if links between atmospheric drivers and precipitation response are to be better understood and projections improved. Whilst the focus here is on one very wet period, the more general point is that it is clearly important to be able to forecast very dry seasons as well as very wet ones; better understanding of atmospheric drivers may enable this to happen (Hartmann et al., 2013).

There is increasing interest in modulation of flood risk by variations in atmospheric circulation at both inter-annual and inter-decadal time scales. In regions affected by the El Niño-Southern Oscillation (ENSO) phenomenon, there are often significant variations in rainfall totals between the El Niño and La Niña phases, for example in the Pacific North West of the USA (Hamlet and Lettenmaier, 2007). In the British Isles, variations in the North Atlantic Oscillation (NAO) can cause large differences in seasonal precipitation totals. This has major implications for river flow: there is increased risk of flooding during wet winters when the NAO is strongly positive (Burt and Howden, 2013) and *vice versa*. There are two reasons why analysis of the historical record remains relevant. Firstly, the apparent increase in flood events needs to be evaluated to assess whether or not it represents a long-term trend or simply shorter-term variability (Pattison and Lane, 2011; Burt and Ferranti, 2012). Secondly, uncertainties inherent in modelling assessments of climate change underline the need for comparison of modelling scenarios with observational evidence (Hannaford and Marsh, 2008). Additionally, knowledge of links between atmospheric circulation and regional climate allows better understanding of causal mechanisms to emerge (Burt and Howden, 2013).

Whilst ocean-atmospheric drivers of hydrology are increasingly investigated using numerical indices such as the NAO Index (Jones et al., 1997) or the Southern Oscillation Index (Ropelewski and Jones, 1987), use of weather types to classify patterns of atmospheric circulation remains a common approach (Pattison and Lane, 2011; Burt and Ferranti, 2012; Jones et al., 2013; Wilby and Quinn, 2013). Reanalyses of historic surface pressure data by major operational weather forecasting centres has enabled objective techniques to be applied consistently back to the 19th century (Kalnay et al., 1996; Compo et al., 2011; Jones et al., 2013). Wilby and Quinn (2013) recommend the use of objective weather indices derived from observed pressure patterns when interpreting fluvial flood risk linked to climatic drivers; they found that the *frequency* of widespread flooding in Britain could be reconstructed with some confidence but not the *magnitude* of events.

Precipitation totals for the calendar year 2012 and for the 2013-14 winter (December to February: DJF) winter provide a contemporary context for this research. The Met Office Hadley Centre's long-running England and Wales precipitation (EWP) series begins in 1766, the longest instrumental series of its kind in the world (Wigley and Jones, 1987; Gregory et al., 1991; Jones and Conway, 1997; Alexander and Jones, 2001). The EWP total for 2012 (1244.4 mm) is the third highest for a calendar year on record, exceeded only in 1768 (1247.3 mm) and 1872 (1284.9 mm). Note that the analysis of rainfall in *England* from 1725 to 1973 by Craddock (1976) also ranked 1872 1st. At Durham, 2012 was easily the wettest calendar year since records began in 1850; the total of 1033 mm is remarkable, more than 100 mm larger than the previous record in 1872 (914.9 mm). In terms of deviation from the 1871-1970 mean (652.3 mm; standard deviation 103.3 mm), these Durham totals represent z-scores of 2.54 and 3.69 for 1872 and 2012 respectively. 2013 was also wetter than average at Durham, although not exceptionally so (764.6 mm, z = 1.09). The 2013-14 winter at Durham was not exceptional, unlike in southern England; Oxford, for example, experienced its wettest ever winter (records from 1767). Matthews et al (2014) concluded that the 2013-14 winter experienced the most severe storminess for at least 143 years when cyclone frequence and intensity were sonsidered together. Notwithstanding what happened in 2012, it is sufficient here to confirm the rarity of the 1872 total at Durham. Moreover, there were other very wet years at Durham in the 1870s and early 1880s: 1882 (850.2 mm) ranks 5th, 1877 (807.1 mm) 9th, 1880 (750.7 mm) 29th, 1878 (749.2 mm) 33rd and 1876 (748.4 mm) 34th.

The 1870s were comparatively early days for rainfall measurements in Britain (Jones et al., 1997a; Parker, 2009). G.J. Symons, who was entirely responsible for setting up a network of rain gauges across the British Isles, paid 1872 particular attention. He commented that the 1872 totals were so greatly beyond the experience of the previous 150 years that he had at first regarded them with incredulity (Symons, 1873). Many stations recorded more than one third in excess of the average of previous years; at Haughton Hall, Shifnal, the 1872 total exceeded the then average (603 mm) by 86%. Of 85 stations with at least 25 years of record, 45 recorded their highest ever annual total in 1872 (Symons, 1873). 1877 was another very wet year but Symons concluded that it did not merit as much analysis as he had devoted to 1872 (Symons, 1878); perhaps there was not quite the same degree of novelty in another very wet year! Scotland was nearly as wet in 1877 as in 1872 but for England, only 4 gauges had higher totals in 1877 than in 1872. With only 1873 being a dry year, it is not surprising that the 1870s as a whole were well above average, the second wettest decade at Durham since 1850 (exceeded only in the 1930s which was wet in the north although not further south). Symons noted that the 1870-79 average was 5% above the 30-year average and grumbled about the effect of large yearly totals disturbing a comparatively short record (Burt, 2009).

The following questions suggest themselves: Why was the 1870s such a wet period? How similar in terms of synoptic climatology was that decade to more recent wet spells? Can we anticipate anything about future weather from analysis of this particular historic period? Whilst precipitation is the main focus of the paper, there is some consideration of river flow too, enabling the precipitation analysis to provide a context for hydrological response (cf Wilby and Quinn, 2013). Whilst the 1870s is the focus of interest, a much longer perspective is needed to place the 1870s in context, hence the use of century-long time series starting in 1871.

2. Data and methods

We used 91 records of monthly precipitation; mostly these were obtained from the Climatic Research Unit (CRU) archive (see Appendix 1) and also Tabony (1980). All begin in 1871 or before and most were maintained at least until the 1970s, meaning that each record was at least 100 years long. These gauges are listed in Wigley et al (1984) and also in Jones (1981, 1983) and Tabony (1980, 1981). We supplemented these data with other very long daily records from Durham (Burt, 2009), Oxford (Burt and Howden, 2011) and Armagh (Butler et al., 1998). Pre-1874 totals for Stornaway were taken from *British Rainfall* for the Isle of Lewis (Stornaway) gauge. Eleven records are included from the Republic of Ireland, allowing coverage of the entire British Isles. Analysis of heavy falls of rain in relation to Lamb Weather types (LWTs) includes some shorter records from northern England referred to in Burt and Ferranti (2012).

Records of river flow are from the UK National River Flow Archive (NRFA: http://www.ceh.ac.uk/data/nrfa/index.html); we used only records for actual river flow and did not include the reconstructed (from rainfall) flow series of Jones et al (2006). Although there are no gauged records for the 1870s, there is anecdotal evidence of widespread flooding in the UK during this period (Chronology of British Hydrological Events: www.trp.dundee.ac.uk/cbhe, see also Jones et al., 1984).

Our analysis of weather types follows Jones et al (2013~~2~~). The “newLWT” dataset is objectively derived: from 1871 to 1947 using the 20CR reanalysis of surface pressure charts (Compo et al., 2011) and National Center for Environmental Prediction (NCEP) reanalysis from 1947 onwards (Kalnay et al., 1996). Lamb (1972) identified 27 possible LWTs which he simplified into seven basic types: anticyclonic (A), cyclonic (C), the four cardinal wind directions – northerly (N), easterly (E), southerly (S) and westerly (W) – and northwesterly (NW). Following Jones et al (2013), we use Lamb’s counting procedure where each pure type (i.e. one of the basic seven) counts one towards the monthly total for the type and then either a half or a third for each of the hybrid types (e.g. northeasterly: NE = 0.5; cyclonic south-westerly: CSW = 0.33). Together with the “unclassified” type, the totals of the seven basic types sum to the number of days in each month. We include ~~simple~~ two simple indices: the difference between annual totals of W and ~~-~~E as an indication of zonality and the difference between annual totals of A and ~~-~~C as an indicator of pressure system dominance. We also include three basic variables derived from the mean sea-level pressure data used in the objective LWT reanalysis: the resultant mean flow strength (F), the total shear vorticity (Z) and the resolved direction of flow (Dir). The flow and vorticity units are geostrophic (each is equivalent to 1.2 knots), expressed as hPa per 10° latitude at 55°N (Jones et al., 2012, Appendix A1); direction is calculated as an angle. Table 1 shows correlations between the various descriptors of atmospheric circulation, including LWTs, objective measures and the NAO. Whilst the results are largely predictable, Table 1 does demonstrate the interdependence between the various indices and we are not aware that such an analysis has been presented before.

We follow Pattison and Lane (2011) in analysing LWTs for days of heavy falls of rain and for days with major peaks in river flow (including the two days before each peak). We use the T10 index of Osborn et al. (2000) to identify heavy falls of rain: this is the daily rainfall total above which the top 10% of total rainfall has occurred (see also Burt and Ferranti, 2012). [Note that Osborn et al (2000) call the T10 index Quantile 10 whilst Maraun et al (2008) call it Category 10.] We use the same approach to identify a threshold for major peaks in river flow. Note that the river flow data are for variable periods; none include the 1870s.

Initial data analysis involves normalisation, calculation of z-scores: a z-score is the number of standard deviations a given observation is above or below the mean. We use data for the period 1871-1970 in order to allow direct comparison between results. Where longer series are quoted (as above for Durham), we continue to use the 1871-1970 mean and standard deviation as a consistent basis for analysis. Where z-scores are calculated for a discrete set of totals, we are able to convert these to probabilities. However, where we calculate z-scores for running-mean totals, these cannot be directly converted into probabilities because the totals are not independent.

3. Results

3.1 Rainfall at Durham in the 1870s

Figure 1a shows annual (i.e. calendar year) rainfall totals at Durham, 1850 to 2013 inclusive. The skewness statistic of +0.062 (adjusted Fisher-Pearson standardised moment coefficient, G_1: Pearson and Hartley, 1970) falls well within the 90% range (G_1=±3.22, n=150) so the distribution can be regarded as normally distributed. Until 2012, 1872 was the wettest year on record, its total of 914.9 mm having a z-score of 2.54; this is equivalent to a probability of occurrence of 0.55% (Arkin and Colton, 1963) or, put another way, a return period of 180 years. The 11-year running mean shows that high totals were sustained throughout the 1870s. The 2012 annual total at Durham (1033 mm) has a z-score of 3.69 equivalent to a probability of occurrence of 0.0112% i.e. a return period of 8920 years. Figure 1b shows the annual count for the cyclonic (C) LWTs from 1871 to 2012. There is a close correspondence: Table 2 shows that the correlation between C and Durham annual rainfall is both strong and highly significant (r = 0.580, p = <0.0001, n = 100). Indeed, as will be shown later, many places show a high correlation between accumulated rainfall totals and the incidence of cyclonic weather. In this regard, it will be noted that 1872 has by far the highest C total (139) for any year since LWT records began in 1871; its W count was well below average (51). [Note that Lamb manually calculated a C total of 100 for 1872, easily highest annual value for C in his series (Lamb, 1972, Figure 16a).] In terms of LWTs, 2012 was similar to 1872, with a below-average average count for W (64) and a high count for C (96). Table 1 shows a significant inverse correlation between C and W (r = -0.338, p<0.001).

For contrast, Figure 1c shows annual precipitation at Fort William. In terms of regional climate, this is a completely different location to Durham. Rainfall across the northwest of Scotland is highly influenced by orographic uplift (Burt and Howden, 2013). Figure 1d shows the annual totals for westerly (W) LWTs, 1871-2012. Notwithstanding generally low W counts in the 1870s, Fort William recorded one of its higher annual totals in 1877; annual rainfall at Fort William has a negative correlation with C count (r = -0.21, p = 0.014, n = 135), significant but not strong in terms of variance explained. In contrast, annual rainfall at Fort William has a highly significant and very strong, positive correlation with W count (r = 0.76, p = <0.0001).

Figure 2 shows the standardised 12-month running rainfall totals (z-scores) at Durham. This confirms the generally high totals experienced during the 1870s, a dry period in 1873-4 notwithstanding. In fact, the highest z-score in the 1870s is not the total to December 1872 but September 1876 – August 1877 (3.15). This was the highest value observed until very recently when 12-month totals in late 2012 - early 2013 were even more extreme. The z-score for the 12-month total to the end of March 2013 (1143.8 mm) is the highest on record (4.49). Only the 1930s have matched the 1870s; indeed the period 1931-1940 (707.1 mm) was slightly wetter per year on average than 1871-1880 (694.1 mm). Other shorter very wet periods have included the late 1960s, late 1970s/early 1980s and the most recent few years. Note that we have not used z-scores here as the assumptions of normal distributions do not apply in the case of running means.

3.2 Mapping z-scores

Figures 3 and 4 show maps of z-scores for 12-month totals to the end of December 1872 and August 1877,respectively. Given that records begin in 1871 and continue for 100 years to 1970, the spatial coverage is surprisingly good. Note that z-scores for both sets of totals are calculated for a discrete sets of 12-month totals (n = 100) and not for the complete series of all 12-month running totals (n = 1200) in order to satisfy the assumption~~s of a normal distribution, in particular the~~ of independence of individual observations. ~~Of course, in practice there will be some small element of autocorrelation between successive "annual" totals but this is very low and can be ignored for the purposes of mapping and descriptive comparison. For example, at Durham, the year to year correlation is r = 0.02 (n =163, p = 0.788).~~

Figure 3 shows that for 1872 z-scores above 3 are found in eastern Scotland and north-east England, the west Midlands, Wales and Northern Ireland. Values below 2 are located in south-east England and western Scotland. The highest value (4.34) is for Braemar, a valley location in the Cairngorm mountains of Scotland; by contrast, the value at Fort William, just over 100 km to the west, is 0.05. This suggests the influence of cyclonic weather producing heavy falls of rain at Braemar, rather than westerlies generating orographic enhancement over the uplands around Fort William (Burt and Howden, 2013). Note that the findings for the orographic rainfall sites of Fort William and north-west England are corroborated by the very long rainfall record reconstructed for the English Lake District (Barker et al., 2004: Figure 6). In that series, 1872 does not even appear in the top five wettest years since 1788. The lowest value plotted on Figure 3 is for Stornaway (-1.4), the only negative value on the map. Other coastal sites in western Scotland have positive but relatively low values: Eallabus (0.68), Stranraer (1.75), Portree (1.44) and Kilmarnock (1.23); Wick on the north coast of Scotland also has a relatively low score (1.73). In Ireland, z-scores are above 3 at northern and south-eastern locations and scores are higher on the west coast than in Scotland (e.g. Valentia: 2.12). The lowest value in the south east is at Kew Observatory (0.87) in London.

Figure 4 shows z-scores for the 12-month period ending in August 1877. The pattern is broadly similar to that shown in Figure 3, although the zone with scores below 2 extends further northwest into the upland Lake District. Further southeast there are values above 2 at Althorp (2.99) and Kew (2.08). Compared to 1872, a number of sites in the West Country have higher z-scores, above 3 for 1876-77 totals. The highest z-scores are again in eastern Scotland at Edinburgh (3.82) and Montrose (3.92). There is a negative value at Fort William (-0.25) and a relatively low value at Eallabus on the island of Islay on the west coast of Scotland (1.19), but Wick on the north coast of Scotland is strongly positive (2.87). In Ireland, z-scores are highest in the south-east, similar to the high scores at western Welsh locations, Pembroke (2.86) in the south and Llandudno (3.43) in the north. Valentia on the SW coast has a score of 2.41, suggesting a higher flow component than in the year 1872, but coastal sites further north in Ireland have scores below 2.

3.3 LWTs in the 1870s

Figure 5a shows annual (calendar year) counts of LWTs for the extended 1870s whilst Figure 5b shows annual rainfall totals for five stations. ~~The dominance of the~~It is clear that wet years correspond with high C counts ~~C count is clear~~, most especially the very large C total in 1872, a year when, not surprisingly, the A count is very low indeed. The C count peaks again in 1877 and 1882, both wet years. Fort William's wettest year is 1877, when high rainfall in that area seems to be influenced by a combination of high C and high W; Appleby and Armagh, both on the west side of the country seem similarly affected.

3.4 Correlations

Twelve-month rainfall totals were correlated with 12-month LWT totals and the average value of the North Atlantic Oscillation (NAO) for the period in question. Results are remarkably similar whether totals were used for the calendar year or for a year ending in August, and whether all available data were used post-1871 or just for the 100 years to 1970 (which maximised comparability of results). Table 1 shows correlations between descriptors of atmospheric flow. Of the objective measures, F is highly correlated with W whilst Z is highly correlated with both A and C (cf. Wigley and Jones, 1987 for correlations between LWTs but not the objective measures of atmospheric flow). DIR has very highly significant positive correlations with E, W, NW and F. NAO is most strongly correlated with W and F. In general, the results confirm that the objective (quantitative) descriptors and LWT counts provide very similar results and that NAO is a good surrogate for measures of westerly flow.

Table 2 shows correlations between annual rainfall totals at selected locations and measures of atmospheric flow. All sites except Fort William are very strongly correlated with A (negative) and C (positive); in relation to the latter and as expected, all gauges except Fort William are also very strongly correlated with Z. Fort William is strongly correlated with F; so too is Malham Tarn in the North Pennine hills, but not Braemar. Fort William and Malham are the only places very significantly correlated with W and also with the NAO; Kew and Crediton are negatively correlated with W at $p<0.01$, the latter being somewhat of a surprise given its south-western location. The frequency of easterlies (E) seems not to be important, even at an eastern location like Durham. There is a significant negative correlation between E and Fort William annual rainfall totals, no doubt indicating the dominance of W at that location (Table 2). Neither index adds much to the analysis: W-E is clearly dominated by W; results for A-C tend to give slightly higher correlations than for A or C alone, but generally all three give very significant correlations everywhere except at Fort William (Table 2). For the sake of completeness, Table 3 shows correlations between the annual rainfall totals for individual gauges. As expected, inter-correlations between sites are very high. Only Fort William is poorly connected, significantly correlated to Appleby and Malham Tarn but not, curiously, with Braemar which is much closer to the east.

Given continued interest in links between UK climate and the NAO (e.g. Burt and Howden, 2013), Table 4 repeats Table 2 for the winter period. The general pattern of correlations is much the same, but there are more highly significant correlations, especially in relation to W, F and the NAO. Note that the negative Durham correlation with NAO is significant at $p<0.05$; this was one of only two stations identified by Burt and Howden (2013) to have a significant <u>negative</u> correlations with the NAO during winter, both in NE England. It is interesting that record length has some influence, even with such long records: the Durham-NAO winter correlation increases to -0.261 for 160 years ($p=0.0008$). For Fort William, there are more significant correlations in winter and those coefficients are closer to one i.e. a stronger effect. Note that in general correlations involving A and C have higher correlation coefficients in winter except for the Braemar-C correlation which is weaker (but still significant at $p<0.001$).

3.5 Daily rainfall totals, peaks in river flow and LWTs

The analysis starts with records where a continuous record of daily rainfall is available from 1871: Durham, Oxford, and Armagh. To this we add Fort William (1928-1964) and Appleby (from 1891) in order to complement the analysis. Coniston Holywath (1937-2007) was added to include another upland gauge, in addition to Fort William, where W was more likely than C to be influential on heavy falls of rain (Burt and Ferranti, 2012; Burt and Howden, 2013). Whilst only the first three can inform the analysis of the 1870s, the others add information about the spatial variation of atmospheric drivers across the UK.

Figure 6 shows the frequency of daily rainfall at Durham above various thresholds – 5mm, 10mm, 15mm and 23.9 mm (T10) – at Durham for the years 1871-1882; results for 2012 are shown for comparison. The categories which show the closest association to annual totals are the smaller, more frequent amounts, in particular 5mm and 10mm, rather than the heavy falls of rain denoted by the T10 index. Table 5 shows the percentage of total rainfall provided by different LWTs at Durham, 1871-2010. Not surprisingly, compared to its overall frequency ("all days" on Table 5), anticyclonic weather provides a low percentage of total rainfall especially for the higher thresholds. The major category providing more frequent and heavier rainfall than expected on the basis of frequency is cyclonic and, to a lesser extent, easterly. For the 15mm threshold, over 50% of days generating such large amounts are classified as cyclonic, even though C days contribute only 19% of the total precipitation (Table 5). ~~Results suggest that the 1872 total was an accumulation of many moderate totals rather than a few, very large ones. The situation seems to have been slightly different in the even wetter 2012 where heavy falls (as indicated by T10 days) were relatively more important.~~ While the frequency of light (<5mm) rainfall is similar in 1872 and 2012, the exceptional total result from an increase in the frequency of heavy falls. Not unexpectedly, the frequency of westerly days providing significant rainfall amounts is lower than expected at Durham, given its location in the lee of the Pennine Hills (Burt and Ferranti, 2012; Burt and Howden, 2013).

Table 6 shows the percentage of rainfall provided by different LWTs at selected locations for the rainfall total thresholds 1mm, 10mm and T10. 10mm was chosen for reasons explained in the previous paragraph but T10 results are included for comparison given that this index is consistent between sites (the daily total above which the top 10% of accumulated rainfall is generated). Of course, a total of 10mm is relatively much more important at somewhere like Oxford or Durham than at the much wetter Fort William. Table 6 shows that C-related rainfall is much more important at lowland sites like Durham and Oxford, and decreasingly important at more western sites like Appleby and Armagh where southerly WTs are most important. At the upland sites, Coniston and Fort William, W airflow dominates. These trends are even more marked for the T10 data compared to the 10mm threshold. For the period 1871-1882, there were 192 days at Durham with 10 mm or more rainfall. Two of those days were "unclassified" in terms of LWT leaving 190 LWT scores. Results are shown by years on Table 7. As expected from Table 6, C-related rainfall dominates, 46% of days in this particular period, a little less than the long-term average shown on Table 6(b); the next highest is S with 18.5%. This pattern is even more extreme for the 15mm threshold (n = 96) in the period 1871-82: C accounts for 49.5% and S only 16%. There are only 25 T10 days in the period 1871-82; for these very wet days, it is interesting that C is relatively less important (39%), with E (19%), S (13%) and W (21%) of more importance. By including analysis of LWTs for all "wet" days (>=1mm), this covers frequency rather than amount. In most cases there is a higher frequency of A and W, and a lower frequency of C, but Fort William and to an extent Coniston show a converse pattern, especially for the T10 index.

Table 8 shows LWTs for peaks in river flow that exceed the T10 threshold together with LWTs for one and two days before the peak; for comparison, LWTs for all days included in the analysis (1956-2009) are analysed for the River Exe. For the Exe, Tees and Tay, C is dominant on the day of peak flow, but W and S are more important in the two days immediately before when the flood hydrograph is likely to have been generated. However, for the largest basin included, the Thames in southeast England, C dominates for day-1, again indicating the importance of cyclonic conditions for widespread rainfall across the lowland east and southeast of the country. The three other basins have substantial areas of upland catchment and much more likely to be influenced by S and, particularly, W airflow. Note that C is a little less dominant for the Tay compared to the Exe and Tees: W dominates all three days with S also important on day-1.

4. Discussion

Burt and Howden (2013) have shown the importance of westerly air flow, as indicated by the strength of the NAO, on precipitation and river flow in the British uplands. However, the results presented here show that over much of the British Isles, heavy rainfall and high rainfall totals are much more likely to be generated by cyclonic weather. This is a very different situation to westerlies generating orographic enhancement over the uplands and will have very different effects. In large river basins with extensive areas of upland catchment like the Exe or Tees, S and W airflow are as likely to generate flooding as C. Moreover, since surface water dominates the hydrology of most upland catchments in Britain, high rainfall totals in winter will be important for filling reservoirs in the uplands (Table 4). This is most likely under strong westerly flow when the NAO is strongly positive (Table 1). In lowland basins like the Thames, flooding is more likely to be generated by C conditions (Table 8). Note that Wilby and Quinn (2013) showed that C-types also yield the most spatially extensive fluvial flooding (as measured by the number of stations simultaneously recording peak flow). For instance, a C-type on 30 October 2000 resulted in 30% of stations recording the annual maximum flow for that water year. In other words, preponderance for C-type weather increases the likelihood of widespread flooding, especially in the English lowlands. These heavy falls of rain generated by C weather will be vital for filling groundwater storage in the Midlands and SE England since groundwater sources are much more important in those lowland regions; winter rainfall is vital in these regions too therefore. Figure 3 and 4 show that large accumulations of rainfall away from the uplands are dependent on a high frequency of C weather. Table 1 shows that C and W LWT scores are inversely correlated, a highly significant r value of -0.338 ($p<0.001$); C and NAO also have a negative correlation ($r = -0.285$, significant at $p<0.01$). Thus, periods when there is a high frequency of C weather, like the 1870s, can be especially important for water resources and flooding in the populated English lowlands. Of course, there will be subtle temporal and spatial differences between periods, as shown in Figures 3 and 4: 1872 was not notably wet in the southeast but the 12-months to August 1877 were much more so, with a z-scores above 2 at several locations including Kew in SW London. In relation to future climate, results suggest that a shift towards more cyclonic circulation would result in higher rainfall totals in the British lowlands. This will have particular significance for rivers like the Thames which have most or all their catchment area in the lowland east (cf Wilby and Quinn, 2013); rivers rising in the upland west are more affected by W and S weather types.

It is of interest to review the days with heavy rainfall during the two very wet periods during the 1870s. Table 9 shows the percentage of LWT scores for days >=10mm at Durham and Oxford for the 12-month periods ending in December 1872 and August 1877. In both periods there was an almost identical percentage of heavy falls from C weather at Durham. What differs is that A and N were relatively more in important in 1872 whilst E and S were more important in 1876-77. It is notable that at Durham W was completely absent in 1872 and a very minor contributor in 1876-77. This emphasises Durham's eastern location in the rain shadow of the Pennine Hills. Burt and Howden (2013) noted that precipitation totals in winter at Durham tend to be higher when the atmospheric circulation is more stagnant. They further speculated that the negative correlation of winter precipitation and NAO at Durham might indicate an enhancement of the rain-shadow effect when NAO is positive (cf. Siler et al., 2013). It follows that the rain shadow should be least evident when NAO is negative and C weather is more frequent. This is certainly the impression gained from Figure 4 where none of the upland areas west of Durham have z scores above 3 and many are below 2. The situation is less clear on Figure 3, at least for Durham, with some upland stations having higher z scores. However, the argument works very well for Scotland in both cases with eastern locations having z scores of 3 or even 4 whilst Fort William's are close to zero. The Oxford rainfall total in 1872 was not especially large (z = 0.81); Table 9 shows that heavy rainfall that year was dominated by cyclonic conditions. In 1876-77, the total was much larger (z = 2.00); C again dominates, but less so than in 1872, and E, S and to a lesser extent A are more influential. As at Durham, W is relatively unimportant for generation of heavy falls of rain at Oxford. It is worth noting that T10 days with W air flow did occur at Durham in 1879 and 1882; this suggests that, under some circumstances, there is little rain-shadow effect and W airflow can generate heavy falls of rain to the east of the Pennine hills. Of course, this discussion has focused on the two very wet periods in the 1870s. However, as Table 2 shows, our conclusions about the dependence of high rainfall totals in the lowlands on the frequency of cyclonic weather are not based merely on two particular years; they conform to a general pattern that is summarised in the century-long correlation analysis.

The very large total at Durham in 1872 was not the product of a few, extreme events. As Table 9 shows, there were more events of 10mm or more in 1876-77; it was the number of days with totals above 5mm that is most remarkable in 1872; as Figure 6 shows, only 2012 has equalled 1872's record total (58). For heavier falls of rain, in comparison to 1872, it is clear that 2012 was even more exceptional: whilst 1872 had four T10 events, 2012 had seven, a record it shares with 1867, 1886, 1888 and 1961. It seems trite to comment that exceptional 12-month totals require most months in the sequence to be above average, but it is not enough to have just a few very wet months. Both 1872 and 1876-77 had 10 months above average; in 2012 the first three months were below average, followed by the wettest 9-month period in Durham's history: all months were above average, some very much so, but none set new records. It seems that there needs to be large numbers of rain days if exceptional totals are to be achieved over the annual timescale.

Unlike places further south, the rainfall total at Durham for the 2013-14 winter was not exceptional; by comparison, Oxford had its wettest winter since records began in 1767. Table 10 summarises LWT scores for the various periods of interest; note that Matthews et al (2014) report cyclone frequency and intensity for the same period. Both 1872 and 1876-77 were characterised by high scores for cyclonic (C) and vorticity (Z) and low scores for anticyclonic (A), westerly (W) and resultant flow (F); there are subtle differences in terms of N, E and S. In contrast, 2012 has higher ranking for W and NW and a somewhat lower ranking for C compared to the two 19th century "years". As well as a high rank for cyclonic weather types, the winter of 2013-14 was characterised by very high scores for both F and Z (cf Matthews et al., 2014), associated with a very strong polar jet stream and a succession of depression systems crossing the country; of course, this is just for a single winter and not for a whole year. Taken together, the results in Table 10 confirm the importance of cyclonic weather for large rainfall totals across much of the British Isles; strong W winds seem only to favour the uplands and the NW coastal regions. Thus, in relation to future climate projections, the 1870s exemplify likely weather conditions during a period dominated by cyclonic weather. Very wet conditions in the lowlands have obvious implications for flood generation but also for water resources, through recharge of aquifers and filling of reservoirs.

5. Conclusions

The very high rainfall totals of 1872, 1876-77 and 2012 were associated with a high frequency of cyclonic weather types and high scores for total shear vorticity; at the same time, the frequency of anticyclonic weather and westerly winds tended to be very low. Places that are normally wettest in the British Isles, i.e. the mountains of the north and west, were not unusually wet at these times, whereas the places with extremely high rainfall totals (relative to mean annual rainfall) tended to be further east, in the lowlands. The winter of 2013-14, remarkably wet in southern England, was somewhat different in that the frequency of westerly weather and the resultant flow were both very high but so too were total shear vorticity and the frequency of cyclonic weather types. It appears therefore that high rainfall over an extended period requires a high frequency of cyclonic weather. Over shorter timescales (i.e. a single season), strong westerlies alone can generate high rainfall in the western uplands whereas a combination of vigorous westerly airflow in tandem with high vorticity is needed to produce exceptional totals in the southern and eastern lowlands.

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Table captions

Table 1. Correlations between measures of atmospheric flow: LWTs, objective descriptors and the NAO. Bold numbers indicate significant at $p<0.001$; italics at $p<0.01$. Data for calendar years 1871-1970 (n=100).

Table 2. Correlations between annual rainfall totals at selected locations and measures of atmospheric flow. Bold numbers indicate significant at $p<0.001$; italics at $p<0.01$. Data for calendar years 1871-1970 (n=100).

Table 3. Correlations between gauge locations. Bold numbers indicate significant at $p<0.001$; italics at $p<0.01$. Data for calendar years 1871-1970 (n=100).

Table 4. Correlations between winter rainfall totals at selected locations and measures of atmospheric flow. Bold numbers indicate significant at $p<0.001$; italics at $p<0.01$. Data for years 1872-1971 (n=100) where "winter 1872" comprises December 1871, plus January and February 1872.

Table 5. Percentage of rainfall provided by different LWTs at Durham, 1871-2012. Rainfall thresholds are in millimetres. Note that rows sum to 100%.

Table 6. Percentage of rainfall provided by different LWTs at selected locations for rainfall total thresholds: (a) 1mm; (b) 10mm; and (c) T10. T10 thresholds are as follows: Durham, 23.9mm; Oxford, Oxford, 22.1mm; Armagh, 20.1mm; Appleby, 24.1; Coniston, 54.8; Fort William, 39.4mm. Period included is 1871-2012 except for Appleby (from 1891), Coniston (1937-2007) and Fort William (1928-64).

Table 7. LWT scores by years for days >=10mm at Durham, 1871-1882.

Table 8. LWTs for peaks in river flow (gauged daily flow, m^3/s) that exceed the T10 threshold. Also given are LWTs for one and two days before the peak and, for the River Exe, LWTs for all days included in the analysis. NRFA station numbers and data periods are: Exe (45001: 1956-2009), Thames (39001: 1883-2008), Tees (25001: 1956-2008) and Tay (15006: 1952-2009).

Table 9. Percentage of LWT scores for days >=10mm at Durham and Oxford for the 12-month periods ending in December 1872 and August 1877. These results correspond to the periods shown on Figures 3 and 4.

Table 10. Ranking of LWT scores for periods of interest. Note that n = 143 except for 1876-77 where n = 142. The highest score is ranked 1.

Figure captions

1. Relationships between Lamb Weather type counts and annual rainfall at Durham and Fort William, 1871-2013. (a) Annual rainfall totals at Durham. (b) LWT count for cyclonic (C) weather types. (c) Annual rainfall totals at Fort William. (d) LWT count for westerly (W) weather types.

2. Standardised z-scores of 12-month running rainfall totals at Durham.

3. Standardised z-scores of annual rainfall totals for the calendar year 1872.

4. Standardised z-scores of rainfall totals for the 12-month period September 1876 to August 1877.

5. Lamb Weather type count and annual rainfall totals at five locations for the period 1871 to 1882. (a) LWT counts with 2012 for comparison. (b) Annual rainfall totals.

6. Frequency of daily rainfall at Durham above various thresholds, 1871-1882.

Appendix 1: List of precipitation stations included in the analysis.

All stations possess monthly totals for the period 1871-1970.

Abbotsinch, Abington, Allenheads, Althorp, Appleby, Ardara, Armagh, Ashbrittle, Askham, Banbury, Barnard Castle, Barrow Gurney, Batheaston, Birr, Braemar, Brecon, Bulland , Cambridge, Cardiff, Cappoquin, Carlisle, Cawston, Cheltenham, Chilgrove, Cirencester, Cork, Crediton, Cullompton, Dublin Airport, Durham, Eallabus, Edinburgh, Enniscorthy, Falmouth, Fort William, Gordon Castle, Hereford, Hull, Hutton, Inverness, Kempsford, Kendal, Kettlewell, Kew, Kidmoor, Killarney, Kilmarnock, Kington, Kirkby, Leeds, Leominster, Lilburn, Llandudno, Loch Katrine, Londonderry, Malham Tarn, Manchester, Mansfield, Markree, Marlborough, Monmouth, Montrose, Mosedale, Newton, Norwich, Nunwick, Outwell, Oxford , Patter, Pembroke, Penrith, Plymouth, Portree, Sarnesfield, Shannon, Shifnal, Simonsbath, South Molton, Southampton, Spalding, Stornaway, Stranraer, Stretham, Taunton, Three Counties, Tiverton, Valentia, Wasdale, Waterford, Whittle Dean, Wick.

Most of these records are available on the CRU website:
http://www.cru.uea.ac.uk/cru/data/UK_IR_rainfall_data/