Field Studies

ANALYSIS OF RAINFALL RECORDS FROM DALE FORT

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ABSTRACT

A composite record of monthly rainfall is presented for Dale Fort Field Centre. The original observations were made in Haverfordwest from 1849 to 1909 and then a series from Stackpole Court was used for the period 1910-1970. The single homogenous series was produced by Dick Tabony at the UK Meteorological Office in 1980 since when the series has been extended using the Dale Fort observations. A daily rainfall record is available for Dale Fort from 1961 and this has been analysed to look at the frequency of measurable rainfall and heavy falls of rain. Some comparisons are made with rainfall inland where there is orographic enhancement of upland rainfall. The wettest day at Dale Fort was 11th October 2005 when exactly 92 mm was recorded.

A BRIEF HISTORY OF DALE FORT

Although there was a proposal for an artillery battery at Dale Fort in 1829, the present fort is a result of a recommendation by Sir John Fox Burgoyne, the Inspector-General of Fortifications, in 1850. Louis Napoleon III had been elected President of France in 1848 and his fighting talk panicked the British government into fortifying the coastal defences of southern England and Wales against an invasion. Sir John Fox Burgoyne, the Inspector-General of Fortifications, recommended that Dale Fort should be built as part of a system of twelve fortifications to deter Napoleon's forces from attacking the Pembroke Dockyard (www.field-studies-council.org/centres/dale-fort).

The battery was originally proposed to prevent an enemy making use of an anchorage at the mouth of Milford Haven. Almost as soon as it was built, there was criticism that the fort was too close to the rock face behind, rendering it potentially untenable during a bombardment; perhaps the criticism stuck since in 1871 it was proposed that the battery at Dale Fort be abandoned and its armament and stores withdrawn (www.victorianforts.co.uk). The fort was completed in 1856 and manned by a garrison of sixty soldiers, along with some of their families. In 1861, Dale Fort mounted seven large (68-pound) smooth-bore muzzle-loading cannons facing out to sea, and two smaller (32-pound) cannons pointing inland to defend against the building being outflanked from the land. By 1870, after the threat of invasion was gone, the garrison was reduced to eleven soldiers and their families. In 1876 there was a recommendation that the fort should be re-armed with larger and more modern guns; however, this was never implemented (www.field-studies-council.org/centres/dale-fort).

In 1902, the fort was sold to Lieutenant-Colonel A. Owen-Evans of the Royal Engineers who converted it into a home for his family. Thereafter, during the First World War, it was the used as a military hospital and a signal station. After the Colonel's death in 1925, the fort was sold to Miss M.A Bland (later Mrs Lee-Roberts). She continued to make improvements to the property, such as introducing an electricity supply and building the glasshouse conservatories.

In 1942, Mrs Lee-Roberts moved out of the fort and it was taken over by the Admiralty who put the fort to various wartime uses. In 1946, the West Wales Field Society purchased Dale Fort, which it then leased to the Field Studies Council (then known as the Council for the Promotion of Field Studies); in 1959, it was sold to the Field Studies Council (FSC). Dale Fort has been run since 1947 as a residential field centre, one of FSC's original "gang-of-four" centres.

WEATHER RECORDS AT DALE FORT

As a result of extensive work on the construction of long rainfall records in the UK in the late 1970s and early 1980s (Jones, 1980, 1981, 1983; Tabony, 1980) numerous long-term and homogenous records of monthly precipitation totals have been developed within the Climatic Research Unit (CRU) at the University of East Anglia and also at the UK Meteorological Office (UKMO), principally for the UK but additionally for a number of locations in the Republic of Ireland. Many sites were developed by Dick Tabony at the Met Office in the late 1970s. A scanned copy this work (Tabony, 1980) is available on the CRU website (https://crudata.uea.ac.uk/cru/data/UK_IR_rainfall_data/); Jones (1983) is available at the same site. Tabony (1980, p230) has an entry for a 'Pembroke' series that is a composite record combining Haverfordwest (1849-1909), Pembroke (1874-1951) and Dale Fort (1951-1975). It seems that CRU re-labelled the Pembroke series as 'Dale Fort' since this is the gauge now used to update the long record. Note that Wigley et al. (1984 https://doi.org/10.1002/joc.3370040102) have a station (their Figure 1, number 42) which is listed as 'Pembroke' (their Table 1) beginning in 1849 and with the same elevation and almost the same location. Tabony's scaling factors to make the record homogeneous do so by scaling the other series to match the Dale Fort one, another reason why it might have been re-labelled as Dale Fort. Table 1, with some minor editing, reproduces Tabony's "Pembroke" entry.

Daily weather reports and daily temperature data are available from 1959 on the UKMO Centre for Environmental Data Analysis (CEDA) website (from the British Atmospheric Data Centre (BADC) Land Surface Stations Database): http://data.ceda.ac.uk/badc/ukmosurface/data/united_kingdom/dyfed/dale_fort.

Daily rainfall records are available from 1961. The CEDA record has been updated from 8/7/1993 to 1/5/2019 using data obtained from Natural Resources Wales (NRW – see acknowledgement below). Three short gaps of approximately monthly length (one in 1993-4; two in 1997) have been infilled using the original UKMO data.

Tabony (1980) constructed a composite rainfall record for "Pembroke" using three gauges from West Pembrokeshire, the most recent record being the Dale Fort record. It is clear that Tabony had access to a Dale Fort record from 1951, a decade before the CEDA/BADC daily record begins. Tabony's first gauge was in High Street, Haverfordwest; it seems that this gauge moved significantly in altitude (and therefore, presumably, location) around 1859/1860. From 1910 to 1970, the Stackpole Court record forms the basis of the homogenised series; there is significant overlap with High Street, Haverfordwest from 1874 to 1909 and with Dale Fort from 1951. The Dale Fort record has provided updates to this long record from 1970 onwards and it is clear that this record is the base to which the other records are adjusted given the conversion used to "correct" the other two records: 0.676 and 0.787 for High Street and Stackpole Court respectively (Tabony, 1980). Finally, it is relevant to note that Tabony's "Pembroke" series was used in the analysis of 1870s rainfall by Burt et al. (2015) without at that time knowing that this was the same series from which the "Dale Fort" series had been developed. Rainfall in the 1870s is discussed in a later section.

British Rainfall gives the height of the Stackpole Court gauge rim above ground level as only six inches (0.15 m) for 1874-77, then one foot (0.30 m) after that. It is not clear what, if any, difference this low level might have made to the amount caught by the gauge; it is probably still too high for significant splash from the ground to enter the gauge. Stackpole Court was latterly the seat of the Earls of Cawdor. The house was demolished in 1963; judging from Tabony (1980) and annual volumes of *British Rainfall*, it seems that rainfall measurement continued until 1970, after which Dale Fort became the series gauge. Here, the Dale Fort records are used from 1961 onwards. Note that the 1955 volume of *British Rainfall* does not include Stackpole Court but the Tabony record is nevertheless complete for the year, so we can assume that the record remained intact but for some reason was not included in that year's volume of *British Rainfall*.

In the course of checking successive volumes of *British Rainfall*, it was noticed that a record exists for St Ann's Head from 1877 to 1950. The measurements were presumably made close to the lighthouse, which is some 2 km SW from Dale Fort. Whilst we have made no use of the St Ann's Head rainfall series, we include the data in the Appendix. There is a highly significant regression between the Dale Fort (DF) annual series and the record for St Ann's Head (STA):

STA = 1.135*DF $R^2 = 0.6361$ n = 74 $p < 0.0001$

It is not clear why the St Ann's Head catch is consistently higher than that at Dale Fort – on average by 13.5% - but Tabony notes that the Dale Fort gauge was sometimes criticised on inspection as "overexposed". For the years when both records existed (1877-1950), the Dale Fort average annual rainfall is 812 mm and for St Ann's Head 924 mm. Note that mean annual rainfall at Dale Fort for the period 1981-2010 is 858.6 mm (Table 2). This is very similar to exposed, western coastal stations in Wales quoted in Sumner (1997): Aberporth: 848 mm and Valley: 843 mm; these are both 1961-1990 averages for which the equivalent figure at Dale Fort is 828.8 mm. It is worth briefly considering two other coastal locations close to Dale Fort for the period 1916-1950, for which the Dale Fort average is 829.2 mm: the average for Skokholm Island was 978 mm and the average at Stackpole Court was 1064.3 mm. It is clear therefore that the Dale Fort average is amongst the lowest on the Welsh coast; this may indicate that gauge is overexposed and therefore has a tendency to under-catch. We are unable to resolve this issue and therefore present the Dale Fort rainfall totals here without any attempt to adjust them.

ANALYSIS OF THE DALE FORT DAILY RAINFALL RECORD 1961-2018

Annual, seasonal and monthly totals

Table 2 presents annual, seasonal and monthly totals for Dale Fort using the current standard averaging period of 1981-2010. Mean annual rainfall at Dale Fort for this period is 858.6 mm, a little wetter than the earlier-period averages quoted above. The 1980s were the second wettest decade since 1849 (896.8 mm average annual rainfall), only exceeded by the 1870s (916.8 mm average: see below). The wettest year since 1961 was 2012 (1159.8 mm total) and indeed this is the second wettest of any year since 1849, exceeded only in 1872 (1198.6 mm). 1964 is the driest calendar year on record since 1961 (645.1 mm total). However, the driest 12-month spell ended in May 1997 with a total of only 474.4 mm; the 12-month total to the end of April 1997 was only marginally wetter: 483.6. The third lowest 12-month total was September 1975 to August 1976, which includes most of the 1975-76 drought including a very dry winter (101.9 mm), the second driest since 1961.

Autumn and winter are the wettest seasons and spring the driest. The wettest autumn on record was 1976 (419 mm), straight after the driest summer (33.2 mm). The second half of 1976 was certainly a time of contrast! Other than 0.2 mm on 11th August, there was no rainfall recorded in the 50 days from 20th July to 7th September. 120.7 mm fell in the rest of September, followed by the wettest October since 1961 (207.7 mm) and a further 91.2 mm in November. Drought soon turned into flood! The 6-month total from September 1976 to February 1977 inclusive is the second wettest on record (772.3 mm), just marginally drier than the six months ending in March 1988 (775.7 mm). Note that the six months from September 1976 to February 1977 were considerably wetter than the entire previous year!

The ratio of winter to summer rainfall is 1.27. As might be expected, given its western location, October, November and December are the wettest months, providing one third of the annual rainfall; January is nearly as wet, so that the period October to January provides 43% of the annual total. The driest months are February through June. Since 1961, the biggest contrast (3.75) between winter and summer has been 1995 when a very wet winter was followed by a hot, dry summer. The biggest contrast between a dry summer and a following wet winter came, not surprisingly, in 1976/77 when the winter was more than ten times wetter than the previous summer!

Daily rainfall

A "rain day" is taken to be any day with a total of 0.2 mm or more. Rain falls on 196 days on average at Dale Fort. Once again, there are more rainfall days in autumn and winter and, given higher totals in these seasons, mean rainfall per rain day are highest in these seasons too. As expected, the highest number of rain days by month are in the period October through January. However, in terms of mean rain per rain day, August has the same value as October, suggesting some influence of convectional activity, even though August is somewhat drier. In terms of heavy falls of rain (expressed on Table 2 as the number of daily totals equalling or exceeding 25 mm each decade), summer and autumn have more or less the same frequency per decade whereas winter and spring have only about half as many. A very similar picture emerges for other indices of heavy rainfall such as the number of daily falls at or above 15mm and the number of falls at or above 22.8 mm, which is the T10 value identified by Osborn et al. (2000); totals equal to or exceeding T10 account for 10% of the total rainfall received.

The wettest day at Dale Fort was 11th October 2005 when exactly 92 mm was recorded. A vigorous frontal trough moved very slowly eastwards across the UK between the 11th and the 13th. Roger Brugge noted that the front moved very little on the 11th, although wave depressions along it did cause some significant variation in the weather. By the end of the day there was flooding in parts of Cumbria and flooding also affected Pembrokeshire and Gwynedd. Schools were shut in south-west Wales with Haverfordwest town centre being badly affected (Brugge: online British Isles weather diary). Philip Eden's weather log for October 2005 noted that torrential rain in many western districts led to serious but short-lived flooding, notably in Wales and Cumbria, and 48-hour totals for the 11th–12th included 140 mm at Milford Haven (Pembrokeshire) and 115 mm at both Eskdalemuir and Carlisle (Eden, 2005). The two-day total at Dale Fort was 109.4 mm (10^{th} + 11^{th}), the highest 2-day total on record. This seems not to have been an event when orographic enhancement was important since the daily total for 11^{th} October at Llysdinam in the Wye Valley was only 22.1 mm.

Ex-tropical depression Charley crossed southern Britain on Bank Holiday Monday, 25 August 1986. At O6OO GMT on 25 August, the surface pressure had fallen to 990 mbar at 49°N l2°W. Over the next 24 hours, the depression moved north-eastwards reaching 52°N 3°W by O6OO GMT on 26 August and deepening to 981 mbar. By the start of Monday rain was already falling in Cornwall and during the rest of the day became widespread as it extended northwards and eastwards, arriving at the coast of north-east England by 2100 GMT. Many places in England and Wales experienced more than 12 hours of continuous, heavy rain and this was reflected in the daily rainfall totals. Aber College Farm, Gwynedd, at an altitude of 15m AMSL recorded 134.9mm. Data from the hourly recording station at Valley, Anglesey, indicate that the rainfall lasted for approximately 18 hours during the period O9OO GMT on the 25th to O9OO GMT on the 26th, and assuming that this was the case at Aber, then the return period for that event is approximately 600 years. The maximum rainfall recorded in one hour was 38.2mm at Preston, Lancashire early on 26 August, with a return period of 200 years (Shawyer, 1987). At Dale Fort the daily total on the 25^{th} was 73.6 mm is the second-highest daily total on record. For Mayes (1986), the most noteworthy aspect of the heavy rainfall in south-west Wales was not so much the absolute peak value but rather the large area that recorded high daily totals (Figure 1). Mayes notes that the unusual aspect of the rainfall distribution was the apparent lack of influence of relief: available data suggest that one of the wettest areas was close to Canaston station (see Figure 1), the elevation of which is only 5 m AOD. The Met Office CEDA database indicates a total of 101 mm at Canaston Bridge. Mayes concludes that much of south Dyfed had falls with a return period in excess of 100 years. The lack of orographic enhancement is shown by a total of only 52 mm at Llysdinam and 57.8 mm at Cantref Reservoir in the Brecons for 25^{th} August.

The third highest daily rainfall for Dale Fort is 64.6 mm on 4^{th} August 2012 enabling mention of 2012, an extremely wet year despite a dry start. The last nine months of 2012 were exceptionally wet across many parts of the British Isles and Dale Fort was no exception. For the period since 1961, this was the highest April-December total on record at Dale Fort (1018.6 mm), easily beating the previous record from 2002 (810.2 mm). Indeed, for the whole record since 1849 (see later), 2012 is the record holder, a good deal higher than the second highest April-December total in 1882 (854.5 mm). Summer 2012 was the wettest on record at Dale Fort since 1849 (366.6 mm) again beating the previous 1882 record (316.2 mm), 198% of the 1981-2010 average. Philip Eden's weather log (Eden, 2012) notes that pressure was low near western Ireland during the first four days of August 2012, with the system gradually drifting across the UK from the 4th–7th. There were frequent showers, sometimes accompanied by thunder, during the first seven days of the month. On the 4th and 5th local flooding was reported in the Scottish Borders, West Yorkshire, Pembrokeshire, the Bristol area and Devon: 40mm was recorded at Chivenor (Devon) on the 4th. At Dale Fort, the total for the 4th was 64.6 mm with another 18.2 mm on the 5th; the combined total of 82.8 mm is the 3rd highest 2-day total at Dale Fort since 1961. For the year as a whole, 2012 was the wettest calendar year on record at Oxford since records began in 1767 (Burt and Burt, 2019); at Dale Fort only 1872 (1198.6 mm) has been wetter than 2012 (1159.8 mm). The 1870s are discussed in more detail in a later section.

OROGRAPHIC RAINFALL IN SOUTH-WEST WALES

When air masses are forced over a topographic barrier, considerable precipitation may accumulate in a very restricted area (Sumner, 1988); this is the so-called ''orographic enhancement effect.'' The generation of orographic rainfall (sometimes called "relief rainfall") is consistent with the feeder-seeder mechanism advanced by Bergeron (1965) in which raindrops from pre-existing clouds aloft ("seeder clouds") wash out small cloud droplets within low-level clouds ("feeder clouds") which form over the hills. The amount of orographic enhancement is determined by the rate at which the low-level flow ascending over the hills can replenish the liquid water content within the feeder clouds. The largest orographic falls can be expected to occur when pre-existing areas of rain associated with fronts and warm sectors are accompanied by strong, saturated low-level flows (Hill et al., 1981).

Given its location at the south-west tip of Wales and the predominance of winds from a south-westerly direction, Dale Fort is an ideal location at which to measure the "upwind" rainfall being provided by seeder clouds before the development of feeder clouds downwind over the Cambrian Mountains. Although Dale Fort is not mentioned in Hill et al (1981), Frank Hill regularly used Dale Fort rainfall as a baseline for judging the development of orographic rainfall to the north-east (Pers. comm. to Tim Burt). In general terms, the generation of orographic rainfall in south-west Wales is very clear. Using 35 gauges listed in *British Rainfall 1990* for a broad transect from Dale to the Elan Valley reservoirs, there is a simple, clear and statistically significant regression between gauge altitude (ALT, m) and annual average rainfall (AAR, mm):

AAR = 1130 + 1.896*ALT, r=0.7, $p < 0.0001$, n=35

Note that AAR in this instance was for the period 1941-1970, for which the Dale AAR was 810 mm, a little less than the 1981-2010 average (Table 1). A small improvement in the regression coefficient is obtained by including "distance east" in a multiple regression analysis (r=0.75) but it remains clear that topography is the dominant control on orographic rainfall in South-West Wales. A rainfall gradient of 189 mm per 100 m is very similar to the gradient of 228mm/100m reported by Harrison (1973, quoted in Taylor, 1976) for a transect further north along the Welsh coast, from the Cardigan Bay coast east to Plynlimon. Unwin (1969, quoted in Taylor, 1976) reported a gradient of 458 mm/100m for Snowdonia, reflecting the steeper, higher nature of the mountains of North Wales. Burt (1980) gives a gradient of 132 mm/100m for the west side of the Southern Pennines, an upland area of similar topography to the Cambrian Mountains but inland from the coast.

Hill et al. (1981) used complementary rainfall radar and raingauge data to explore the detailed processes involved in the generation of orographic rainfall; these measurements were made when the use of rainfall radar was very much in its infancy. Their observations cover the period 28 November 1976 through to 9 February 1977. Since their observational periods lasted only a few hours, it is not possible to provide an exact comparison here using daily rainfall totals, but the comparisons are of interest nevertheless; we use daily totals from Dale Fort, Garreg Ddu reservoir in the Elan valley and Cantref Reservoir in the Brecon Beacons. Hill et al (1981) graded eight events from one (the greatest enhancement of surface rainfall intensity) to eight (the least enhancement). The daily totals do not show the same gradient but the comparisons with Dale show totals up to up to six times greater in the hills (Table 4). It is clear that using daily totals is not ideal; hourly rainfall data together with radar sequences would allow individual storms to be identified as they move inland from the coast.

Finally, as an example of a single rainfall event, note that Figure 1 shows that the rainfall associated with ex-tropical depression Charley indicates only a small degree of orographic enhancement over the hills to the north-east of Dale Fort. Modest relief to the east of Haverfordwest clearly generated some extra rainfall compared to at the coast but there is then no great addition moving towards higher ground. This is probably because the rainfall was already very heavy at the coast with little opportunity for additional rainfall from low-level feeder clouds.

THE LONG RAINFALL RECORD FOR DALE FORT FROM 1849

Figure 2 shows the annual rainfall record for Dale Fort from 1849, together with a decadal running mean. There was a steady increase in annual rainfall from the start of the record through to the 1870s, a notably wet decade. Burt et al. (2015) used traditional Lamb Weather Type count and objective measures of atmospheric circulation obtained from reanalysis of surface pressure charts to classify the weather conditions under which these very high rainfall totals in the 1870s were generated (Table 5). 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 in the 1870s (relative to mean annual rainfall) tended to be further south. 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. It is interesting to note that the year 2012, already discussed above, experienced similar atmospheric conditions to the 1870s. Burt et al. (2015) compared data across different sites for the period 1871-1970. In their analysis, the wettest 12-month period at Dale Fort was the calendar year 1872 (1198.6 mm, z score = 3.00) followed by September 1876 – August 1877 (1188.1 mm, z = 2.91). For the complete series 1849 – 2018 (Table 6), the wettest 12-month period is September 1987 – August 1988 (1263 mm, z = 3.57) followed by April 2012 – March 2013 (1253.8 mm, z = 3.33) which of course includes the very wet, final 9 months of 2012, the wettest 9-month period on record and the only 9-month total to exceed 1000 mm (1018.6 mm).

Rainfall totals declined after the wet year of 1882: Marsh et al. (2007) identify a “long drought” from 1890-1910 for England and Wales. The Dale Fort series shows the 1910s (806.9 mm) were only a little wetter on average than the 1900s (779.8 mm) and the 1890s (754.2 mm). This was a major, protracted drought therefore but with some very wet interludes, 1903 especially. The drought was initiated by the very dry winter of 1891 and the 1890s were characterised by very dry springs. There were then some very wet years in the 1920s after which average annual totals remain steady around 800 mm. The next wet period was from 1980 through to 1994, after which totals declined through to 2001 from where they have begun to increase on average again. Whilst summer rainfall has tended to increase in recent years, winter rainfall has increased even more, so that the winter-summer ratio has been increasing after falling through the 1980s and 1990s (Figure 3); the decadal running mean for the winter-summer ratio reached its lowest point in 2007.

Figure 4 shows the decadal running means for the four seasons. There is a good deal of variability over the long period of record but in general terms spring behaves opposite to autumn and winter, whereas summer seems to have its own pattern of changes. No doubt the recent rise in summer rainfall, as denoted by the most recent decadal averages, is unduly influenced by the exceptionally wet summer of 2012, easily the wettest summer on record (366.6 mm). Only five summers have exceeded 300 mm in total since 1849: 2012, 1882 (316.2 mm), 1879 (312.2 mm), 1860 (306.1) and 1985 (303.3 mm). Excluding 2012, the decadal summer average is below 200 mm through the 2010s. Most climate projections suggest wetter winters and drier summer in future, but it is clear that very wet summers can still occur. At the other end of the plot, Figure 4 shows that the very wet 1870s were the result of a combination of very wet autumns and winters, with some very wet summers too, towards the end of the decade.

SYNOPTIC ORIGINS OF RAINFALL

Table 5 shows the correlation between annual rainfall at Dale Fort and selected climatic indices as used by Burt et al. (2015). There is a strong positive link to the frequency of cyclonic weather and therefore a strong negative correlation with the frequency of anticyclonic weather. It may seem surprising that there is no correlation with the frequency of westerlies, but this seems to be a feature only found only at upland sites further north. The very wet year 1872 has the highest count for cyclonic weather for any calendar year since Lamb Weather Type records begin; its westerly count is well below average (Burt et al., 2015). None of the gauges listed by Burt et al (2015) had a correlation with the frequency of the southerly LWT, but this is evident at Dale Fort with a correlation of $r = 0.282$, significant at $p < 0.01$. The frequency of the southerly LWT is positively correlated with flow strength ($r = 0.261$) and inversely with cyclonic LWT ($r = -0.176$). The result at Dale Fort may indicate a distinctive element of rainfall generation for western coastal locations and would seem to merit further investigation. It may provide an important element of upwind seeder-cloud rainfall.

When correlating seasonal rainfall totals with the North Atlantic Oscillation (NAO) index, only one correlation is significant: for summer rainfall, the correlation is -0.17 ($n = 169$, $p = 0.026$). These results are typical for many places in southern Britain, including western coastal locations. Significant correlations with NAO in other seasons tend to be found in upland locations and at more northerly coastal locations such as Stornaway and Lerwick (Burt and Howden, 2013).

CONCLUSIONS

With a mean annual rainfall below 900 mm, Dale Fort has one of the lowest rainfall totals for a westerly coastal location in the British Isles, very similar to the Scilly Isles in fact (The 1941-70 AAR at St Mary's was 881 mm). Rain falls at Dale Fort on average every other day; interestingly, it only rains an extra 30 days at Cantref Reservoir in the Brecons for double the rainfall! Dale Fort thus provides a useful upwind rainfall record to compare with orographic enhancement over the Cambrian Mountains. It would be instructive to be able to compare hourly rainfall records in the future, in order to identify conditions under which the greatest rates of orographic enhancement occur. The long Dale Fort composite rainfall series provides one of the longest rainfall records for Wales. Significant variability at the decadal timescale resulted in a very 1870s and a much more recent wet period in the 1980s and early 1990s. There was a significant drought at the end of the 19th Century and in the first two decades of the 20th Century. Notwithstanding a tendency for wetter winters and drier summers, the very wet summer of 2012 reminds us that not all summers will be dry in a warmer world.

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Table 1. A transcribed, slightly modified copy of Tabony (1980, p230) for the "Pembroke" long rainfall record, now known as the "Dale Fort" record, showing how Tabony constructed a single, homogenous record using three separate long records from West Pembrokeshire.

H = gauge altitude (m), h = height of gauge rim above ground (m), d = diameter of gauge orifice (m).

PEMBROKE

510840 51°48′N 04°59′W Haverfordwest, High Street

Period	H	h	d	Remarks
1849-1859	18	0.6	0.13	
1860-1909	29	0.3	0.13	1870. On plot of grass, 1.2 m square, in a garden open to NE and W, but rather sheltered to the S.

508139 51°37′N 04°55′W Pembroke, Stackpole Court

Period	H	h	d	Remarks
1874-1889	18	0.5	0.13	
1890-1899	18	0.5	0.15	
1900-1903	18	0.5	0.20	
1904-1951	18	0.5	0.15	1926 Inspection: Gauge in middle of large flat garden surrounded by walls 5-6 m high. Trees outside walls 18-21 m high. Gauge on oak stand, and projects 5 cm above top of stand. 1967 Inspection: Gauge moved ± 3m according to crop being grown.

511627 51°42′N 05°10′W Dale Fort

Period	H	h	D	Remarks
1951-1975	33	0.3	0.13	Regular inspections: either satisfactory or overexposed

Homogenised record

1849-1909	Haverfordwest	x 0.676
1910-1970	Pembroke, Stackpole Court	x 0.787

Comments

The overlapping ratios are for the periods 1874 to 1909 and 1951 to 1970

	Average rainfall (mm)	Max. total (mm)	Min. total (mm)	Rain days (>=0.2 mm)	Max. number rain days	Min. number rain days	Mean rain per rain day (mm/rain day)	No days >=25 mm per decade	Max. daily rainfall (mm)
January	84.3	182.0	12.5	20	29	5	4.2	1	40.6
February	58.4	139.0	2.1	16	26	2	3.6	1	37.0
March	64.5	157.8	10.7	17	25	7	3.6	1	36.6
April	54.9	142.2	9.9	15	26	3	3.8	1	37.6
May	53.6	120.5	4.6	14	24	5	3.7	1	28.0
June	52.7	121.6	6.2	13	25	3	4.1	1	34.2
July	60.0	184.2	2.7	13	25	3	4.4	2	40.8
August	72.6	165.6	0.2	15	27	1	5.0	4	73.6
September	68.5	147.4	10.6	15	26	3	4.5	3	57.6
October	97.8	207.7	19.3	20	29	8	5.0	3	92.0
November	98.9	209.6	29.8	20	28	10	4.8	2	62.8
December	92.5	179.1	21.5	19	29	7	4.8	2	52.6
Winter	235.5	429.2	97.0	55	79	29	4.2	4	52.6
Spring	172.9	278.6	59.6	46	62	22	3.7	3	37.6
Summer	185.3	366.6	33.2	41	63	16	4.5	7	73.6
Autumn	265.3	419.0	78.2	54	75	31	4.8	8	92.0
Annual	858.6	1159.8	645.1	196	245	146	4.3	22	92.0

Table 2. Monthly, seasonal and annual rainfall statistics for Dale Fort, 1961-2018. All averages are for the period 1981-2010.

Rank	year	month	day	data
1	2005	10	11	92.0
2	1986	8	25	73.6
3	2012	8	4	64.6
4	1982	11	5	62.8
5	2015	9	14	57.6
6	1968	12	24	52.6
7	2011	10	24	48.8
8	2018	11	6	46.6
9	1999	8	24	45.6
10	2015	8	22	45.2
11	1961	8	7	43.2
12	1970	11	6	42.4
13	2014	8	9	41.6
14	2009	7	16	40.8
15	1968	1	8	40.6
16	1972	8	7	40.4
17	2002	10	13	39.8
18	1987	10	17	39.7
19	1979	10	3	39.1
20	1972	11	12	39.0

Table 3. Largest daily rainfall totals recorded at Dale Fort since 1961.

Event	1	2	3a	3b	4	5	6a	6b	7	8
Date (1976/77)	28 Nov	2/3 Feb	24/25 Jan	25/26 Jan	6 Feb	26 Nov	1/2 Feb	2/3 Feb	9 Feb	27 Nov
Wind speed (ms^{-1})	29	27	23	26	21	21	19	17	21	14
Wind direction	230	220	205	230	245	235	220	230	190	260
Dale Fort	9	8	7.9	5	5.1	2.1	4.1	8	30.7	6.9
Cantref	20	25.6	23.9	13.4	19.7	10.5	7	25.6	26.5	24.8
Garreg Ddu	20.4	34.1	6	29.5	16.1	9.3	10.8	34.1	21.8	22.6
Cantref: Dale	2.22	3.20	3.03	2.68	3.86	5.00	1.71	3.20	0.86	3.59
Garreg Ddu: Dale	2.27	4.26	0.76	5.90	3.16	4.43	2.63	4.26	0.71	3.28

Table 4. Comparisons of daily totals at Garreg Ddu and Cantref reservoirs with Dale Fort for eight events observed by Hill et al (1981). The Cantref raingauge is at 341 m altitude, AAR 1895 mm. Garreg Ddu raingauge (Nantgwillt church) is at 234 m, AAR 1603. Data from *British Rainfall 1990*; AAR values for the period 1941-1970.

Year	A	C	N	E	S	W	NW	A-C	W-E	Z	F	DIR
-0.072	**-0.611**	**0.523**	-0.012	0.081	*0.282*	-0.051	-0.104	**-0.628**	-0.070	**0.606**	0.129	-0.076

Table 5. Correlations between annual rainfall totals at Dale Fort and measures of atmospheric flow. These results supplement those listed in Table 2, Burt et al. (2015). Bold numbers indicate significant at $p<0.001$; italics at $p<0.01$. Data for calendar years 1871–1970 ($n=100$). Seven basic Lamb weather types (LWT) are used: anticyclonic (A), cyclonic (C), the four cardinal wind directions – northerly (N), easterly (E), southerly (S) and westerly (W) – and north-westerly (NW), plus two simple indices: the difference between the annual totals of W and E as an indication of zonality and the difference between the annual totals of A and C as an indicator of pressure system dominance. Also included are 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).

Date	12-month total	z-score
August 1988	1263.0	3.57
March 2013	1235.8	3.33
December 1872	1198.6	3.00
August 1877	1188.1	2.91
October 1930	1186.2	2.89
October 1960	1171.4	2.76

Table 6. Peak 12-month rainfall totals at Dale Fort since 1849. Three months with very similar totals have been omitted: July 1988, September 1988, February 2013.

Figures

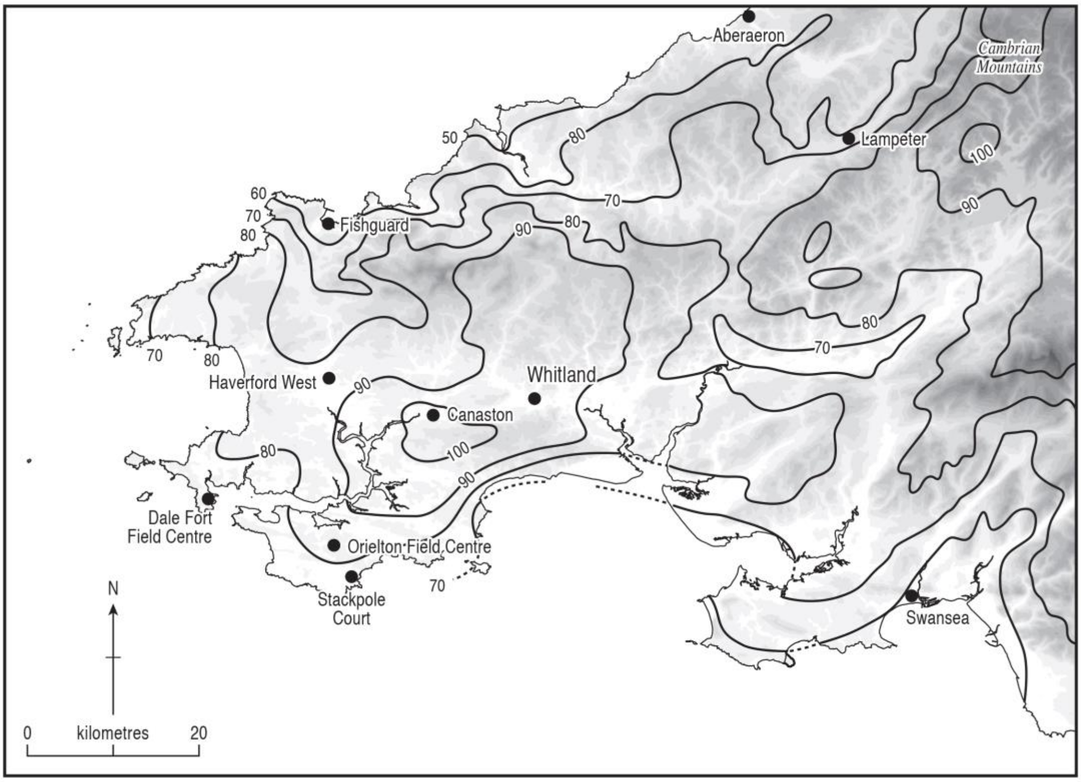

Fig 1. Daily rainfall totals (mm) in south-west Wales associated with Hurricane Charley, 25 August 1986 (redrawn from Mayes, 1986).

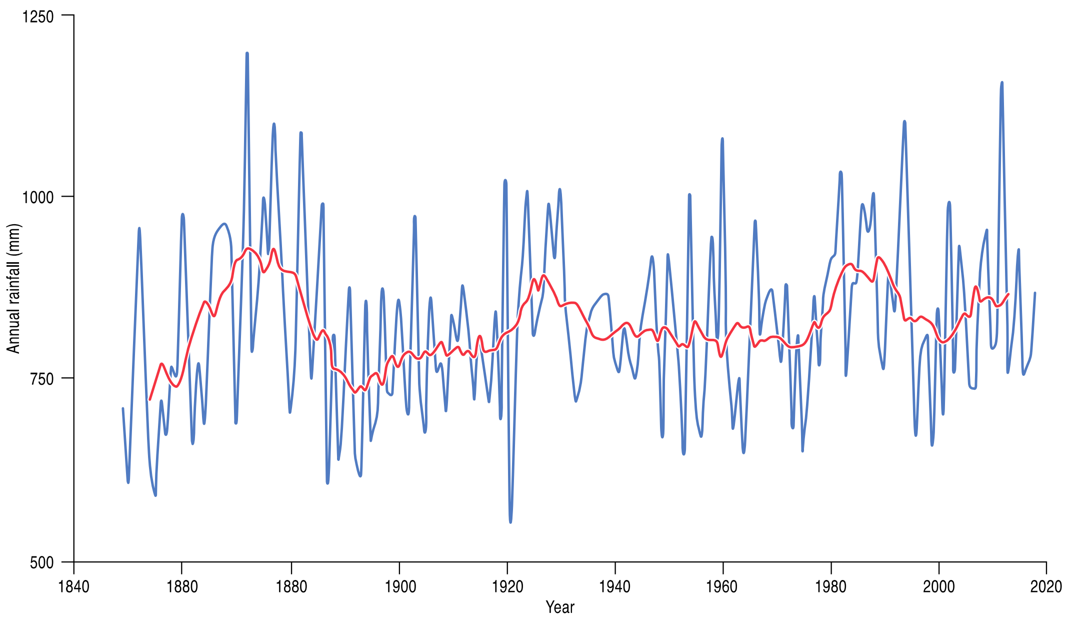

Fig 2. Annual rainfall totals (mm) for the Dale Fort composite series from 1849 together with a decadal running mean.

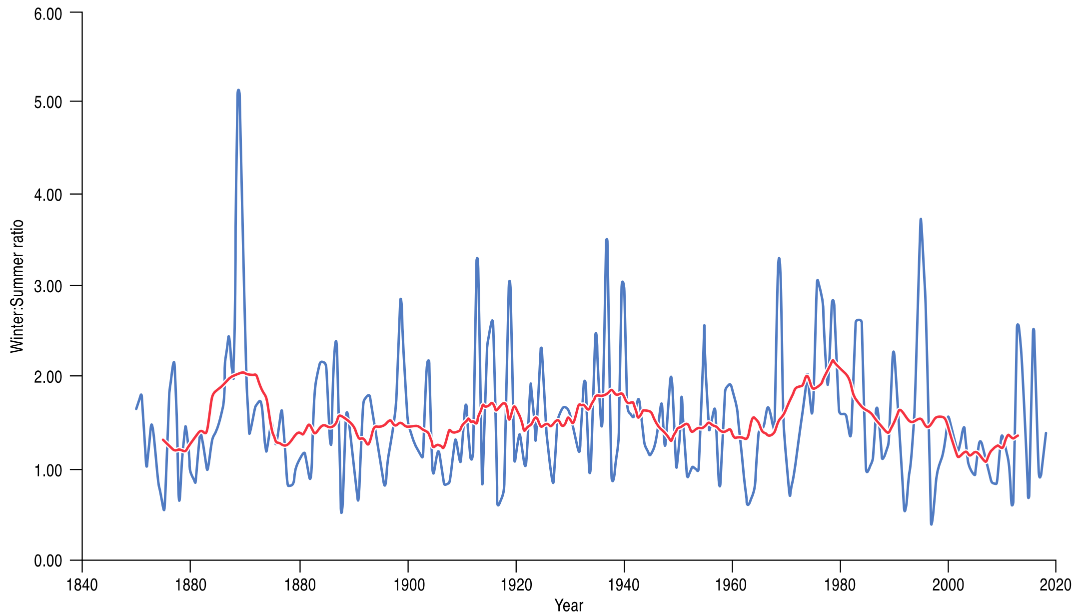

Fig 3. The ratio of winter to summer rainfall for the Dale Fort composite series from 1849.

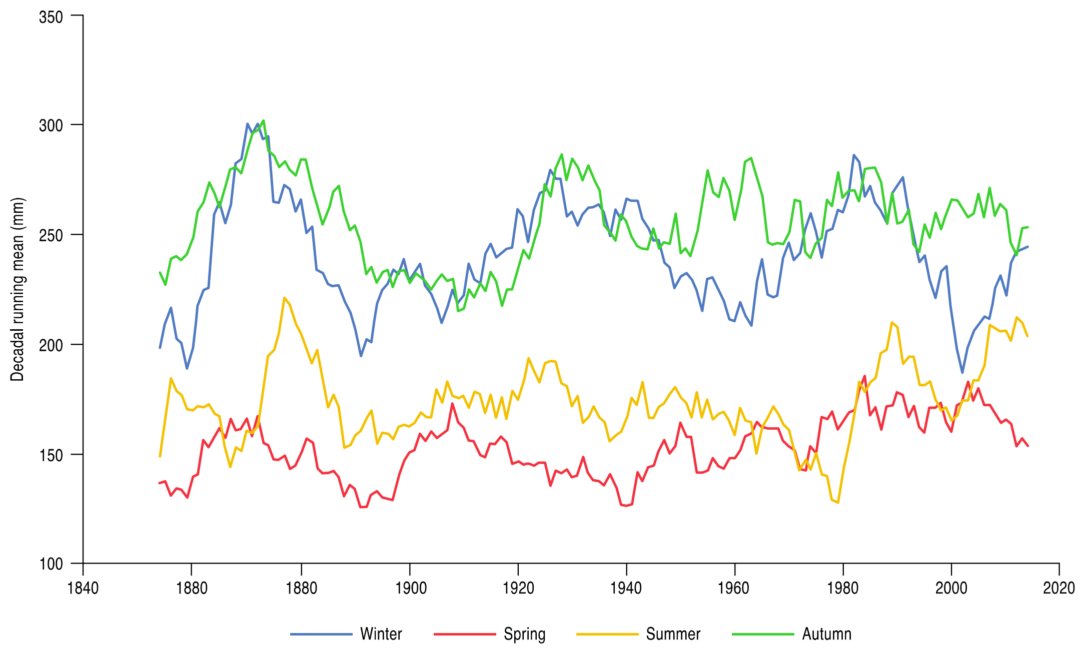

Fig 4. Decadal running means for the four seasons.