A twice-daily barometric pressure record from Durham Observatory in north-east England, 1843-1960

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A twice-daily barometric pressure record from Durham Observatory in north-east England, 1843–1960

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Abstract

A twice-daily record of barometric pressure exists for Durham Observatory (54.768 °N, 1.584 °W, barometer cistern 107.3 m above mean sea level, MSL) from 23 July 1843 to 31 December 1960 and is published here for the first time. The Durham record, which is 98.7% complete, is by far the longest digital barometric pressure series in northern England and fills a very large temporal and spatial gap in the International Surface Pressure Database (ISPD: Cram et al, [2015] *Geoscience Data Journal*, 2, 31–46). In what is believed to be the first study of its kind, the record has been independently quality-controlled against the NOAA–CIRES–DOE Twentieth Century Reanalysis version 3 (20CRv3; Slivinski et al., [2019] *Quarterly Journal of the Royal Meteorological Society*, 145, 2876; Slivinski et al., [2021] *Journal of Climate*, 34, 1417–1438), which did not include the Durham records in its assimilation set. This paper describes the instruments used and their exposure, the sources of the record, digitization work undertaken to generate the digital time series (including quality control assessments using 20CRv3) and reduction to mean sea level pressure from station level observations, and examines consistency over the period of record against 20CRv3, concluding with a summary of monthly and annual means and extremes over the 117 year series and the details of the new dataset.

KEYWORDS

20CRv3, barometric pressure series, Durham Observatory, quality control, reanalysis

Dataset

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1 | INTRODUCTION AND METADATA

The astronomical observatory at Durham University (Figure 1, Figure 2) opened in 1840 and commenced meteorological observations shortly afterwards. Astronomical observatories such as Durham required observations of barometric pressure and external air temperature to correct star positions for atmospheric refraction (Burt & Burt, 2019, Chapter 5), and for this purpose high-quality instruments were usually procured from reputable manufacturers. Information on the barometers used, their calibrations and their exposure within Durham Observatory, has been assembled from original archival records held in Durham University Library together with previously restricted Met Office site inspection reports and correspondence held in the Met Office Library and Archives in Exeter.

The first details we have of Durham's barometer are from the monthly climatological return to the Met Office for January 1877, when the barometer's serial number was given (209). The earliest surviving Met Office site inspection record for Durham Observatory, for September 1902, adds the detail that barometer 209 was a Fortin-pattern instrument made by Browning. Brownings were a long-established optician and scientific instrument-maker, trading in London from the early 19th century; the business advertised itself as 'Optical and physical instrument-maker to Her Majesty's Government, the Royal Observatory [Greenwich] and Kew Observatory' (Banfield, 1991; Meliconi, 2004).

At this distance in time it is impossible to state with certainty whether the Browning barometer noted as being in use in 1877 and 1902 was the original station barometer in use when the Observatory opened in 1840/41, but it is certainly possible; it is equally possible that the Browning barometer replaced an earlier instrument in June 1867, as a very brief comment ('New barometer installed') appears in the observations register at that time, although no equipment receipts or other metadata confirming a possible change of instrument have yet been found (Durham University Library, 2016).

Although there were occasional temporary substitutions by other instruments as detailed subsequently, this barometer remained in use between at least January 1877 and termination of the record in December 1960.

In 1910, and probably earlier, the barometer was located at the side of the eastern window on the first floor of the Observatory (Met Office inspection report, 1910)—Figure 2. The height of the barometer cistern above MSL was stated as 352 ft or 107.3 m throughout the record. Thereafter, only minor relocations of the instrument took place.

FIGURE 1 The location of Durham Observatory, and other locations referred to in the text

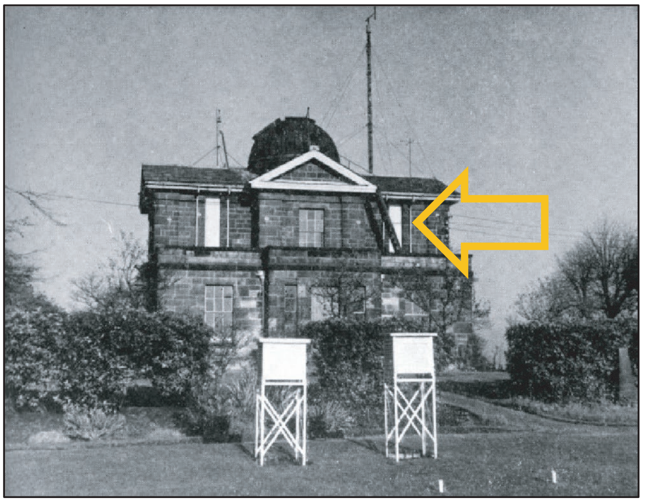

FIGURE 2 Durham Observatory, photographed in 1955. The observatory's barometer was located behind the eastern window (arrowed). Photograph from Baxter (1956)

Until 1949, the barometer was checked against a standard mercury barometer carried by the inspector at every Met Office inspection (conducted at typically 2–3 year intervals); errors were found to be small, within ±0.1 or 0.2 hPa.

From the beginning of the record, the observed ('As Read') barometer readings, in inches of mercury, at the morning and evening observation hours are given in the original registers, together with the barometer temperature (the 'Attached Thermometer'), the latter in degrees Celsius to March 1867, thereafter in Fahrenheit until November 1948, after which the 'Att. Therm' entry was omitted from the registers. The 'corrected' reading of the barometer (here referring to correction for the thermal expansion of the mercury column from room temperature to the standard 0°C, rather than the correction to MSL pressure), usually referred to as the 'station level pressure', is also included in the observation registers until November 1948. This correction was made by reference to a local table, not always accurately, and for consistency during the preparation of the series the correction to 0°C was recalculated using the observed Attached Thermometer reading, in preparation for reducing the 'station level pressure' so obtained to 'mean sea level pressure' (as documented below). The 1910 inspection report noted that a minor index correction from the Browning barometer's calibration at Kew Observatory was included within the table used within the observatory to reduce the barometer reading to 0°C, and the recalculation of 'station level' pressures adopted here will therefore not include this. However, the barometer was recertified on 14 January 1925 following minor cleaning and repair work, after which the corrections applied were all noted as 0.1 hPa or less across the working range of the instrument (1926 inspection report). The effect of the omission of the corrections is therefore probably insignificant.

From early 1948, the barometer readings appear to have given cause for concern, because the mean 0900 and 2100 GMT MSL pressures were not published in the *Monthly Weather Report* after February 1948. It is probably no coincidence that the Browning Fortin barometer was removed for cleaning and repair (by Negretti & Zambra) in December 1948. A Kew pattern barometer, on loan from the Met Office, was read in its place until 31 August 1949 (September 1949 inspection report refers). This barometer was graduated and read in millibars.

The original Browning Fortin barometer returned to Durham in September 1949 and remained in use until the cessation of the record on 31 December 1960, except for the five months 28 August 1957 to 28 February 1958 when it was again away for cleaning. Records during this period were from a temperature-compensated aneroid barometer on loan from the Met Office, and accordingly there are no 'Attached Thermometer' readings. The Fortin barometer was recertified by Negretti & Zambra on 5 February 1958 and brought back into use from 1 March 1958.

From September 1949, the barometer readings in the register continue in millibars, suggesting that the Fortin barometer had been refitted with a new scale during its cleaning and repair. The barometer at this date was at least 80 years old, and quite possibly over 100. The reading of the Attached Thermometer was omitted from the observation register from this point, as examined in more detail subsequently.

Unfortunately, there is no record of what happened to the Browning Fortin barometer following the discontinuation of readings in December 1960, and its current whereabouts are unknown.

2 | INSTRUMENTAL RECORD SUMMARY

2.1 | Observation hours

From the commencement of record until September 1885, hours were reckoned by local or 'common' time, about 6 minutes later than the Greenwich Meridian, but from October 1885 onwards Greenwich Mean Time (GMT) was adopted as the observatory's standard time. The barometer readings were noted for the majority of the period of record at 09h and 21h daily, the exceptions being as follows:

Morning observation:

- At 10h, February 1855 to September 1885.
- At 09h Summer Time (07h GMT) during operation of Summer Time, 1916–1918.
- At 09h Summer Time (08h GMT) during operation of Summer Time, April to September 1945 (letter in site file, Met Office Archives, dated 30 September 1945).

Evening observation:

- No evening observations were made between February 1855 and June 1858; instead, a 14h observation was made during this period.
- At 22h, July 1858 to September 1885.

Occasional observations at other 'non-standard' times such as 2140h have been assumed to be 'late observations' from the intended hour and simply included without adjustment along with the other observations for the 'standard' hour.

2.2 | Missing data

The record is remarkably complete; for the period July 1843 to December 1960, 117 years, 98.7% of observations appear in the database. The main gaps (four or more consecutive missing observations) are shown in Table 1.

TABLE 1 Missing data in the Durham Observatory pressure series, July 1843 to December 1960

Period missing	No. of days	Period missing	No. of days
4–8 Aug 1845	5	24–31 Dec 1883	8
1 July to 14 Aug 1854	46	6–8 Oct 1908	3
27 Sept to 7 Nov 1854	43	5–16 Feb 1923	12
7–12 Dec 1854	6	9 March to 17 April 1923	39
27 Dec 1854 to 14 Feb 1855	51	10 Oct 1934 to 28 Feb 1935	143
1–11 Feb 1856	11	1 April to 31 May 1935	62
1–6 June 1865	6	1 June to 31 Aug 1936	92
		12–15 June 1960	4

2.3 | Units

Until November 1948, barometer readings were stated in inches of mercury (inHg), to two places of decimals until 23 March 1846 and thereafter to three places of decimals (0.001 inHg = 0.03 hPa). These have been converted throughout to hectopascals (hPa: 1 hPa = 1 millibar; 1 inHg = 33.86388 mbar) and rounded to 0.1 hPa after the application of any corrections. From December 1948 onwards, observations were noted in millibars. Attached thermometer readings are stated in degrees Fahrenheit or Celsius at various times: all have been converted to degrees Celsius. On the database, both 'station level pressure reduced to 0°C' and the calculated mean sea level (MSL) pressure are given in hPa for each available observation. The method used to reduce station level pressures to mean sea level is detailed below.

3 | CREATION OF THE DURHAM PRESSURE DATABASE

3.1 | Digitization of the record

Most of the original manuscript meteorological records from Durham Observatory have been retained, either in the Department of Geography or in the Durham University library. An initiative funded by the Leverhulme Trust saw many of the manuscript instrumental records from 1850 to 1997 digitized (Kenworthy et al., 1997), although until recently knowledge of this dataset remained almost entirely limited to Durham University. The barometric pressure observations (which terminated after December 1960) were included in this project—fortunately, for the Durham pressure record now represents by far the longest digital barometric pressure series in northern England, filling a very large gap in the International Surface Pressure Database (ISPD: Cram et al., 2015). The ISPD forms the majority of the input to the NOAA–CIRES–DOE Twentieth Century Reanalysis version 3 (hereafter 20CRv3; Slivinski et al, 2019, 2021), currently extended back to 1806. The remaining early records, from July 1843 to December 1849, were digitized by hand in 2021.

3.2 | Errors in the series

Unfortunately, the 'Leverhulme Trust' barometric pressure record as originally digitized contained a significant number of major errors, some of which were due to the original observers and some due to mis-digitization. An understanding of the causes leading to typical errors enables the process of checking and correcting to be more efficiently undertaken. Pressure records in inch units tend to exhibit distinct and characteristic errors, which can be briefly summarized as follows:

3.2.1 | Observer errors in reading the instrument, or noting the observation

The typical scale of barometric pressure in the United Kingdom covers the pressure range from below 28 to above 30 inHg. It was very common in manuscript entries in inch pressure registers to omit the inch value until and unless the integer changed, by entering only the values following the decimal point. The transition from one inch integer to another can easily be omitted by the observer, as Table 2 indicates.

In line 6, the entry '30' has been omitted, implying that the observed pressure is 29.013 inHg rather than 30.013, and this leads to a 1 inHg error (33.9 hPa) in the digitized value. The '30' entry then appears correctly in line 7, but the '29' entry has been omitted from the following line, leading to a large positive error in the converted inch value. This type of error is particularly common where the average station level pressure is close to 30 inHg (1015.9 hPa), and thus the changeover of leading digits from '29' to '30' or vice versa happens frequently. Where the observations are close together in time, such as hourly or three hourly records, correction is usually a matter of simple

TABLE 2 Example of common errors in barometric pressure entries in manuscript register

Observation	Manuscript entry inHg	Digitized as inHg	Conversion to hPa	Correct inch values	Conversion to hPa	Error hPa
1	30 106	30.106	1019.5	30.106	1019.5	
2	062	30.062	1018.0	30.062	1018.0	
3	004	30.004	1016.1	30.004	1016.1	
4	29 994	29.994	1015.7	29.994	1015.7	
5	906	29.906	1012.7	29.906	1012.7	
6	013	29.013	982.5	**30.013**	1016.4	**33.9**
7	30 042	30.042	1017.3	30.042	1017.3	
8	981	30.981	1049.1	**29.981**	1015.3	**−33.9**

Note: The bold values indicate errors resulting from the omission of the prefixed inHg value in the original observation entry.

continuity checks to flag as suspect any particularly rapid rises or falls which are immediately followed by a similar magnitude fall or rise. Where observations are spaced 6–12 hours or more apart, as is the case with Durham, great care is required to avoid false corrections as changes of 30 hPa in 6 hours or more, rises or falls, do occur from time to time, particularly during the winter months.

3.2.2 | Incorrect reading of the 0.5 inHg vernier scale

Most inch barometers have a major division at 0.5 inHg intervals, and it can be easy to misread (say) 29.72 for 29.22 inHg, thereby introducing a 16–17 hPa error. These errors are much harder to spot on a twice-daily or daily record, but comparison with 20CRv3 and manual examination of the relevant synoptic chart, where available, often helped determine whether the observation value was correct or otherwise.

3.2.3 | Incorrect or unclear digits in the observations register

There are many possible errors here—confusions between 0, 6 or 9, 1, 4 or 7, 2, 4 or 7, and 3, 5 and 8 are typical, and often mistaken for each other at the digitization stage if the written record is in any way unclear. Any such errors will generally only be obvious where they amount to at least several hPa from the 20CRv3 background, and thus are difficult to identify and correct.

3.2.4 | Incorrect entry in the register

It is very easy to enter, say, 29.852 inHg in the register when the barometer was read as 29.582. Such errors are almost impossible to identify and correct unless the noted observation value differs by at least several hPa from the 20CRv3 background.

3.2.5 | Incorrect transcription of any of the above errors during digitization

Incorrect transcription of any of the above errors during digitization will produce similar results. Some are easy to spot by out-of-range checks, especially errors in the inch value itself; digitized values of 20 inHg or 39 inHg are easy to flag and clearly incorrect, but whether the true value in such instances should be 29 inHg or 30 inHg may not be immediately obvious. Such cases require close consideration of the context of the record including, where possible, examination of the original register entry.

3.2.6 | Incorrect millibar entries

For the millibar records (from December 1948 to end of series), occasional errors in reading the scale persist; most appear to be around ±10 mbar (hPa), or multiples thereof.

3.3 | Correction to mean sea level pressure (MSLP)

For the period 1843 to 1948, reduction of the observed or 'As Read' barometer readings to MSL involved a two-stage process; firstly, to correct for the observed temperature of the barometer (the 'Attached thermometer' reading) to the standard 0°C, this value referred to as the 'station level pressure'; and secondly to correct the derived station level pressure to mean sea level (MSL), for which the outside air temperature (dry bulb temperature) is also required. From 1949 onwards, the value of the incremental MSL correction was derived at the observatory and noted in the observations register, and thus has been used to correct the 'As Read' pressure to MSL. Further details are given in Section 4.3 below.

A detailed account of the rationale for, and the methods involved in, the reduction of barometric pressure to MSL is beyond the scope of this paper, and the reader is referred to specialist texts, such as the *Handbook of Meteorological Instruments, Volume 1: Measurement of atmospheric pressure* (Met Office, 1981) and the World Meteorological Organization CIMO observing guide (WMO, 2018), Chapter 3, *Measurement of atmospheric pressure*. At the Durham Observatory, only the station level pressure was required for astronomical work and MSL pressure was not routinely evaluated until January 1949, and thus is not included in the manuscript observation registers prior to that date.

Throughout, calculations were performed in an Excel spreadsheet.

3.3.1 | Correction to 0°C

For a Fortin barometer, and for pressure in millibars, the barometer temperature correction in millibars per Kelvin is 0.163 mbar/K at 1000 mbar 'As Read' pressure. The correction is proportional to the 'As Read' pressure and is negative for Attached Thermometer readings above 0°C or 273 K (Meteorological Office, 1956, Chapter 2, *Atmospheric Pressure*). Thus, for 'As Read' 1020 mbar and Attached Thermometer 20°C, the correction is −3.32 mbar and the station level pressure at 0°C becomes 1016.68 mbar. The calculation is slightly different for a Kew barometer and is closer to 0.171 mbar/K at 1000 mbar. Normally no correction for barometer temperature is required for aneroid instruments, such as the temperature-compensated aneroid barometer in use at the Observatory for five months during 1957–58.

Prior to 1955, standard corrections for barometer temperature assumed a barometer temperature of 62 °F (17 °C) and standard gravity 9.8062 m/s^2; correction tables based upon these values (or even earlier standards) would most likely have been used for most of the Durham pressure record. To ensure the application of consistent corrections to modern standards, and to bypass occasional errors in the observation record and the digitized series, the entire Fortin 'As Read' record prior to 1949 was corrected to 0°C using the post-1955 standard.

3.3.2 | Reduction to MSL

The reduction to MSL is computed in two stages. The first is to sum the barometer's index errors (calibration differences at various pressures) together with the correction for standard gravity of 9.806 65 m/s^2, which varies with latitude, and then add this to the station level pressure as calculated above. This sum is then added to the MSL correction term to obtain the MSL pressure or MSLP.

The index errors for the barometer in use are not individually known, although inspection reports stated they were small, and accordingly they have been neglected in this calculation. The correction for standard gravity at the Observatory's latitude (54.768 °N) at 1000 mbar is +0.83 mbar (Table LIIA in Meteorological Office, 1956, page 439) and is in proportion to the station level pressure.

The method of reduction to MSL follows that set out by WMO in the CIMO guide, section 3.7 (WMO, 2018) as follows, assuming a constant lapse rate:

$$p_{\mathrm{msl}} = p_{\mathrm{stn}} . \exp\left(\frac{\frac{g}{R}.H}{T + \frac{L.H}{2} + e_s.C}\right)$$

where the terms are as follows: p_{msl} is the MSL pressure (in hPa); p_{stn} is the station level pressure (hPa); g is the standard acceleration of gravity (9.806 65 m/s^2); R is the gas constant of dry air (287.05 J/kg/k); H is the station elevation (in geopotential metres—the error in using altitude in metres is insignificant and can be neglected below about 500 m AMSL. For Durham Observatory, the barometer cistern height of 107.3 m was used); T is the outside air temperature (in Kelvin), from observed dry-bulb temperature in °C T_C +273; L is the assumed lapse rate in the fictitious air column extending from sea level to the level of the barometer cistern, taken as 0.0065 K/gpm; e_s is the station vapour pressure (in hPa) and C is a coefficient (0.12 K/hPa).

In this calculation, the station vapour pressure e_s is taken as 85% of the saturation vapour pressure e_{sat} at the outside air temperature T_C (in °C)—(i.e. the humidity is taken as 85%, very close to a true mean for Durham[1]). e_{sat} is calculated using the formula due to Bolton (1980), which is acceptably accurate between −30°C and 35°C:

$$e_{\mathrm{sat}}(T_c) = 6.112 \exp\left(\frac{17.67T_c}{T_c + 243.5}\right).$$

The value of the MSL pressure thus obtained was then subjected to quality control measures as set out below.

[1]Whilst we do have dry- and wet-bulb temperatures for almost all observations, it would require a great deal of additional computation to calculate relative humidity and vapour pressure for each observation, for no significant benefit to the MSLP calculation. Averaged over a year, the difference between MSLP assuming RH 75% and RH 95% (accounting for the majority of diurnal and seasonal variations) is about 0.01 hPa, which is much lower than instrument and observer errors, and can therefore be safely neglected.

4 | APPLYING REANALYSIS DATA TO EFFECT QUALITY CONTROL OF THE DURHAM MSLP SERIES

Without some form of independent record, it would be difficult to provide objective assessment of the accuracy and reliability of the new Durham series, particularly at the daily or sub-daily level. Fortunately, the increasing accuracy and lengthening timescale of reanalysis datasets provide an objective means to assess record quality; this is believed to be the first time an underpinning assessment using reanalysis has been applied to verify an independent long-period pressure dataset. Alternative methods include comparisons against gridded MSLP series or weighted comparisons with other sites. Clearly there is the potential for circularity in the correction of the candidate series against 20CR if and when the corrected series is subsequently assimilated into the reanalysis at a later date. However, the risk of circularity in this case is considered to be very small, firstly because the reanalysis series was only used to flag potential errors, which were then followed up wherever possible by scrutiny of the original registers or other sources (such as the online Met Office *Daily Weather Report* and subsequent publications), and secondly because the number of flagged errors is very small, amounting to just 0.42% of the entire series between 1843 and 1960 (Table 3). The published database also includes both 'raw' and 'post quality control' values, as well as the 20CRv3 gridpoint ensemble mean MSL value for the nearest interval to the observation time.

Reanalyses can provide complete and consistent atmospheric fields by objectively combining historical observations with modern numerical weather prediction model forecasts, while accounting for estimated errors in both (Kalnay et al., 1996). The latest version of the Twentieth Century Reanalysis (20CR) has been generated by the University of Colorado Boulder's Cooperative Institute for Research in Environmental Sciences (CIRES) together with the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Energy (DOE). This NOAA–CIRES–DOE 20CR version 3, 20CRv3, uses a newer, higher-resolution model, assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessors. The 20CRv3 system further extends the reanalysis period to 1836–2015, with an experimental extension spanning 1806–35. Slivinski et al. (2019) provide an in-depth description of the system that generated the 20CRv3 reanalysis product, which consists of a numerical weather prediction model, an observational dataset and an assimilation method. Using an 80-member ensemble Kalman filter, the 20CRv3 system assimilates only surface pressure observations (a so-called 'sparse' reanalysis) from the open, unrestricted and publicly available International Surface Pressure Databank (ISPD) version 4.7 (Cram et al., 2015; Compo et al., 2019), into the U.S. National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model, with a horizontal resolution of about 60 km at the equator and a vertical atmospheric resolution of 64 levels. Sea surface temperature and sea ice, solar radiation and time-varying atmospheric constituents of volcanic aerosols, stratospheric ozone and atmospheric carbon dioxide (CO_2) levels are also specified. Output fields are available at 3-hourly resolution.

Until very recently, there were no pressure records from sites in England held on the ISPD (and thus available to the 20CRv3 reanalysis) prior to 1925. Before 1925, the only ISPD records within the British and Irish Isles are those from Armagh in Northern Ireland (pressure data from 1796 to 1826, 1833 to 1965; Figure 1), Aberdeen in Scotland (1871 to 1948, 1957 to 1988) and Valentia Observatory in the Republic of Ireland (1892 to date). Recent work by Hawkins et al rescued pressure data from Fort William and Ben Nevis from 1883 to 1904 (Hawkins et al., 2019) and digitized records from multiple European sites published in the UK Met Office contemporary *Daily Weather Report* publication from 1860 (Lewis, 1982; Craig and Hawkins, 2020); this work has been completed, although at the time of writing it has not yet been incorporated into ISPD. Consequently, the accuracy of atmospheric reanalyses over the north-eastern Atlantic prior to 1925 has been constrained owing to the dearth of reliable surface pressure records in and around the British and Irish Isles. This newly available record from Durham should therefore be helpful in assessing both likely errors in gridpoint pressure data from the reanalysis ensemble means, and changes over time, and in improving the accuracy/reducing ensemble spread in future reanalyses once the Durham data are eventually included into ISPD and a future version of 20CR.

4.1 | Method

A time series of pressure values (ensemble mean pressures) at a given gridpoint can be obtained from the 20CRv3 reanalysis website (https://psl.noaa.gov/data/timeseries/hour/), for any period within the main dataset (currently 1836–2015). This output, in the form of one or more sub-daily gridpoint ensemble mean pressures at 3 hourly intervals (00, 03, 06 GMT, etc) for the chosen period, was used to provide an independent underpinning quality control measure to the Durham MSLP record (the two series can be regarded as independent since the Durham series was not included in the ISPD datasets from

TABLE 3 Durham pressure record QC summary, comparing 'raw' (original digital dataset) and 'Post QC' (after quality control measures as described in the text). A positive value in the 'Average arithmetic error' indicates that the Durham value is higher than the 20CRv3 gridpoint ensemble mean value, and vice versa

Period and number of observations		No. of corrected observations	Average arithmetic error 20CRv3 minus Durham, hPa	Error Std Dev'n hPa	Average RMS error 20CRv3 minus Durham	MSLP average, hPa	% values 20CRv3 ±2 hPa	% values 20CRv3 ±10 hPa
Fortin barometer July 1843 to Nov 1948								
Raw	75 816 of 76 964 (98.5%)	None	+0.43	11.15	2.21	1013.35	64.5	99.0
Post QC	75 827	319 (0.42%)	+0.34	2.71	1.97	1013.26	64.6	99.4
Kew barometer Dec 1948 to Aug 1949								
Raw	548 of 548 (100%)	None	+0.47	1.38	1.05	1017.53	89.2	99.6
Post QC	548	2 (0.36%)	+0.43	1.22	1.01	1017.49	89.6	100.0
Fortin barometer Sept 1949 to Dec 1960 excl. 28 Aug 1957 to 28 Feb 1958								
Raw	7901 of 7910 (99.9%)	None	+0.59	1.85	1.23	1013.48	85.9	99.4
Post QC	7901	28 (0.35%)	+0.63	1.29	1.13	1013.51	86.7	100.0
Aneroid barometer 28 Aug 1957 to 28 Feb 1958								
Raw	370 of 370 (100%)	None	+0.54	1.76	1.16	1012.66	85.4	99.5
Post QC	370	2 (0.54%)	+0.45	1.34	1.08	1012.58	85.9	100.0
Combined record, July 1843 to Dec 1960								
Raw	84 646 of 85 792 (98.7%)	None	+0.45	10.56	2.11	1013.38	66.8	99.1
Post QC	84 646	352 (0.42%)	+0.37	2.60	1.88	1013.30	66.9	99.5

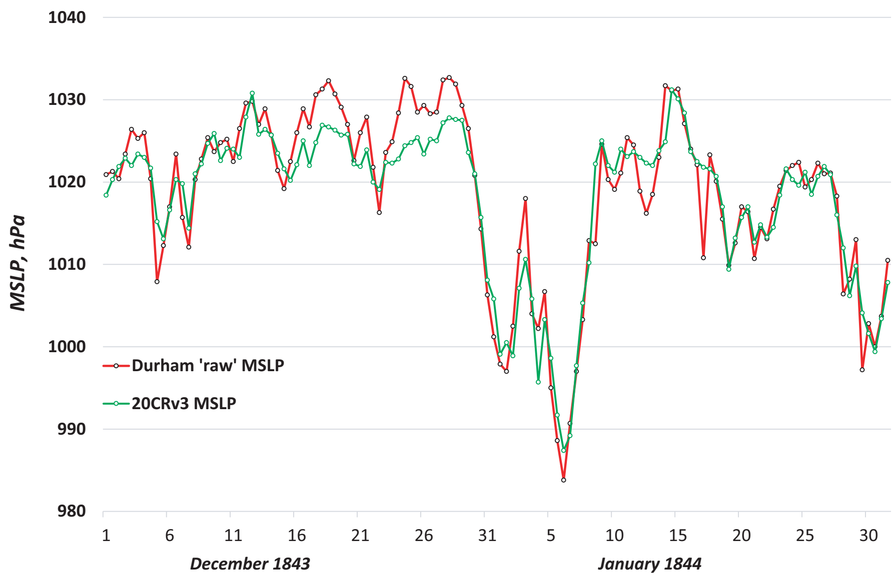

FIGURE 3 Comparison of daily 'raw' (uncorrected) Durham MSL pressure observations at 09h and 21h solar time (6 minutes later than Greenwich time) (red line) with 20CRv3 nearest gridpoint values at 09 and 21 GMT (green line), for the months of December 1843 to January 1844, the first winter of the record. The very close agreement is evident, and the few significant differences are most likely due to uncertainties in the reanalysis—see text for details

which this version of the reanalysis was built). The nearest 20CRv3 gridpoint to Durham Observatory is at 55°N 2°W, about 36 km north-west of the observatory (54.768°N, 1.584°W). Gridpoint ensemble mean pressure values were extracted for 0900 and 2100 GMT[2] throughout the period of record, except for February 1855 to June 1858 when an afternoon observation was made at 1400, for which 1500 GMT gridpoint values were used instead.

An example, from the first winter of the record in December 1843-January 1844 and using observed (i.e. pre-QC) data, is shown in Figure 3. The tendency for ensemble averaging to reduce the absolute range in extremes is evident in the plot. This is understandable when it is considered that the assimilation of this version of the reanalysis is based upon only a single site in the British and Irish Isles at this time (viz. Armagh, Figure 1), and consequently the spread of ensemble members is likely to be less constrained than in later periods with a denser spread of surface pressure observations.

When Durham's observations were made at 10h and 22h, 0900 and 2100 GMT gridpoints were also used as representing the closest point in time. The resulting 20CRv3 twice-daily gridpoint pressure series was then compared against the Durham MSLP record.

Of course, no quality control measure can ever render an imperfect record into a perfect one, and it is important to minimize changes to the original record commensurate with removing at least the most obvious errors. The 20CRv3 daily and sub-daily series are particularly useful where short spells of observations are missing or have been mis-coded with incorrect dates, for pattern-matching (by eye or by algorithm) can quickly suggest a fitting sequence. However, as Table 3 shows, the vast majority of the Durham record appears extremely reliable. In turn, the independent Durham dataset provides a useful benchmark to assess the likely accuracy of 20CRv3 within the north-east Atlantic region.

Figure 4 shows both the annual mean root-mean-square (RMS) and absolute errors (the arithmetic difference 20CRv3 gridpoint minus Durham) over the period of 1844 to 1960. From this it is evident that the relative accuracy of the reanalysis dataset usually increases over time, as would be expected with increasing density of assimilated surface pressure data. The one significant exception to this fairly smooth trend occurs between 1914 and 1919, when the Durham data provide clear evidence of a previously unknown bias in 20CRv3 over the North Atlantic. This anomaly has since been confirmed by examination of other reanalysis products and two UK pressure series; at the time of writing, the reasons for it remain unclear and under investigation (Ed Hawkins, Clive Wilkinson and Gil Compo, personal communications February-March 2021).

The Durham pressure series is divided into four periods and each discussed in more detail below.

4.2 | July 1843 to November 1948

At just over 105 years in length, this comprises the first and longest subdivision of the Durham pressure series. As far as can be ascertained, the record originates from the same instrument throughout, namely the Browning Fortin barometer. The series is 98.5% complete; most of the gaps after 1883 resulted from periods when the Browning instrument was away for cleaning or repair.

Throughout this period, the twice-daily series appears extremely reliable when compared against the relevant

[2]Strictly, GMT as a defined time standard did not exist until 1885, but for convenience times are referred to as GMT for dates prior to 1885 unless otherwise stated.

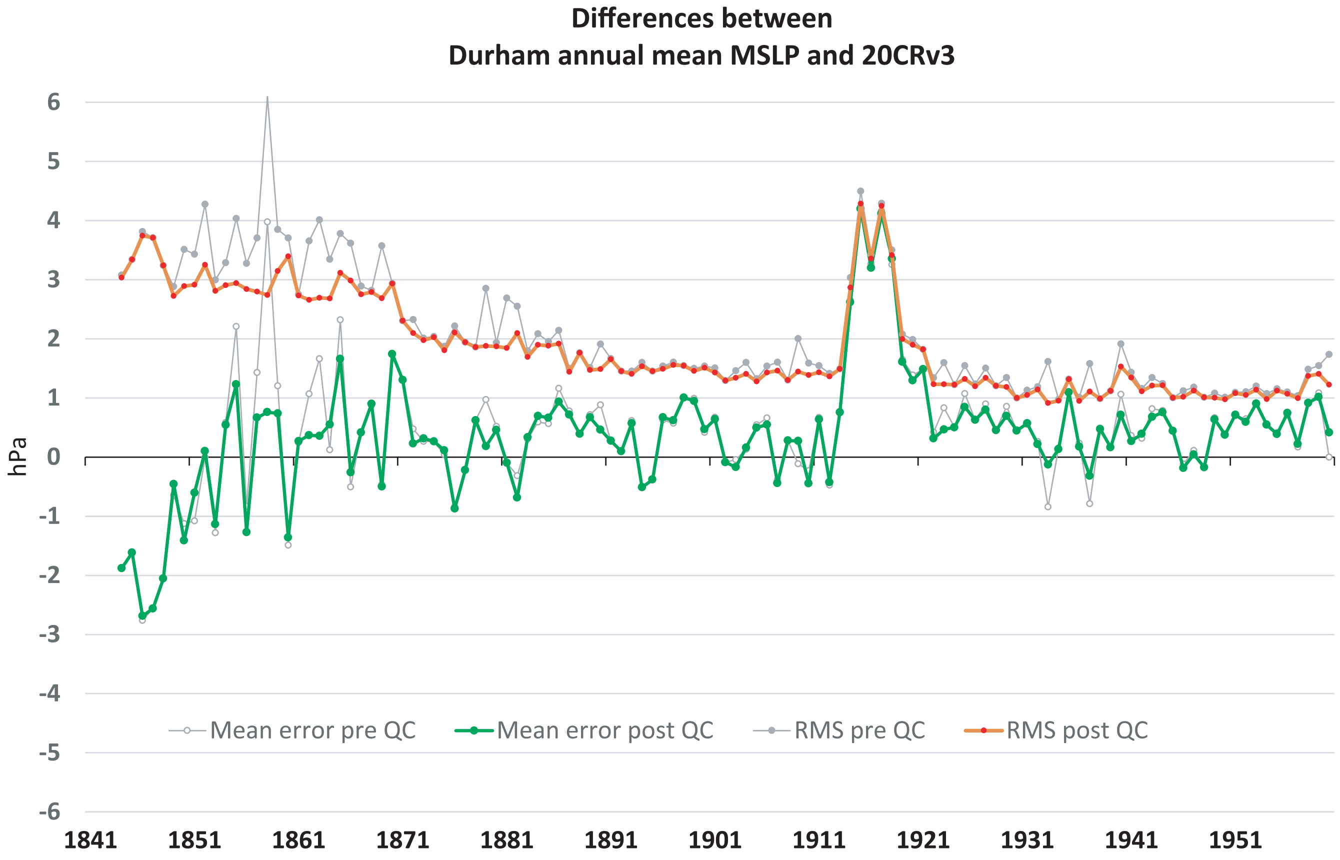

FIGURE 4 Annual mean arithmetic (green line) and root-mean-square RMS errors (orange line) between the quality-controlled Durham pressure series and 20CRv3 nearest gridpoint value, 1844 to 1960. For comparison, the thin grey lines on both series show the arithmetic mean and root-mean-square errors from the uncorrected (pre-QC) series

20CRv3 gridpoint value (Table 3 and Figure 4). Even prior to the introduction of quality control corrections, between July 1843 and November 1948, 64.5 per cent of the available observations lay within ±2 hPa of the corresponding 20CRv3 gridpoint value, and 99.0% lay within ±10 hPa. Comparisons against 20CRv3 suggested that 319 records (just 0.42% of the total observations) were most likely to be incorrect.[3] Most of these (235, or 73%) were found to be clustered close to 0.5 or 1.0 inHg multiples, thereby suggesting an error in the 'As Read' reading as the most likely cause: a few were 9 or 10 inHg errors (i.e. an entry of 20 or 39 inHg instead of 29 or 30 Hg). Such discrepancies are almost certainly due to one or a combination of the reasons outlined earlier. The distribution of errors was Gaussian and almost symmetrically distributed about zero, as is evident from the very minor change in mean MSL pressure (Table 3). The post-QC Durham mean pressure is slightly higher than the 20CRv3 gridpoint mean—for the whole 111 year period by 0.37 hPa—as would be expected with the gridpoint being 36 km north-west of the Observatory location and the expected climatological decrease in mean MSL pressure with increasing latitude in the British and Irish Isles.

An automated quality control check against 20CRv3 was successful in flagging most if not all of the major errors during this period, increasing the number of the Durham observations within ±10 hPa of the corresponding 20CRv3 gridpoint value from 99.0% to 99.4%. However, objective automated error checking became progressively less reliable with smaller discrepancies. At errors below roughly 17 hPa/0.5 inHg difference, the very high quality of most of the Durham series would suggest that the difference is more likely to arise from errors in the reanalysis field, particularly prior to about 1925 for reasons referred to earlier. The two most likely causes of such errors are timing differences (almost always cyclonic storms moving or developing more quickly than suggested by the reanalysis model), and insufficient deepening of intense cyclonic systems within the reanalysis. In particular, the latter effect clearly resulted in some Durham records being incorrectly flagged

[3] The 'error' in this sense refers to the difference (20CRv3 gridpoint value minus Durham). Such differences can arise only through an error in the Durham value (whether observer, transcription or subsequent digitisation), or uncertainty in the 20CRv3 reanalysis field. The latter is larger in the early years of the record where fewer surface pressure observations have so far been assimilated.

as erroneous, when a manual check on the original manuscript records (at present, online files available for 1843–1850 only), or from observations published in the relevant *Daily Weather Report* from September 1860 (and, later, synoptic charts from March 1872), showed that they were almost certainly correct—in which case, the error flags were removed and the original observations reinstated.

Whilst it would be easy enough automatically to correct all discrepancies larger than, say, ± 10 hPa by arbitrarily assuming the Durham value was in error and flagging it as 'incorrect', and of course doing so would immediately reduce the number of errors larger than 10 hPa from 0.6% to zero, it was felt that such actions would almost certainly result in some valid observations being wrongly flagged as incorrect. Accordingly, to avoid arbitrary corrections to the Durham series, for this period quality control checks were applied only where the discrepancy was greater than about 15 hPa, or where smaller errors could be investigated by manual checking against other nearby sites (usually from stations included in the *Daily Weather Report*) or by other methods, such as continuity checks in periods of settled weather conditions. Particular attention was paid to records close to or exceeding monthly long-term climatological extremes.

In time, it should be possible to check all discrepancies greater than, say, ±5 hPa back against the original manuscript observation registers to identify and correct any mistyped digitization entries. Unfortunately, coronavirus travel and access restrictions made this impossible during the preparation of this paper, but when this step becomes feasible, it will be possible to re-examine and correct the Durham series as necessary.

In summary, therefore, the first and longest part of the Durham pressure series appears impressively complete and shows a very high degree of accord with the 20CRv3 reanalysis. Most if not all of the larger errors have been identified and corrected, but it is likely that an unknown number of smaller errors remain in this period of record. While some uncertainty remains with regard to individual values, monthly and annual means over this 107 year period are believed to be correct to within a few tenths of a millibar.

4.3 | December 1948 to December 1960

The barometer in use during the final 12 years of the long Durham record changed several times, as stand-in instruments were used in place of the Browning Fortin unit whilst away for cleaning and refurbishment in 1948–49 and 1957–58 as detailed below.

The period is sub-divided by barometer type in use; the distinction is important because the detail of the corrections applied to the observed value differs somewhat according to the type of barometer, and these have been allowed for in the MSL corrections applied. From December 1948, all barometer readings were made in millibars; with the change of graduation comes a change in the nature of 'major' errors, which are now more likely to be about ±10 mbar, or multiples thereof.

Readings of the 'Attached Thermometer' ceased with effect from 1 December 1948. From January 1949 onwards, the entry in the Att Therm column in the observations register appears to be the incremental MSL correction to the As Read value, presumably derived from a barometer correction card taking the barometer temperature into account in doing so (the method is explained in the *Handbook of Meteorological Instruments, Volume 1: Measurement of atmospheric pressure*; Met Office, 1981). Although a different MSL derivation scheme for the final years of the series is unfortunate, the absence of the observed Att Therm reading renders this a necessity and from January 1949—with exceptions listed below—the MSLP was taken as As Read +MSL correction as given in the observations register. For the few occasions when the correction was missing, estimates based on neighbouring observations were used.

4.3.1 | December 1948 to August 1949: Kew Barometer

A loan Kew-pattern barometer replaced the Browning Fortin barometer while the latter was away for repair between December 1948 and August 1949. This barometer was graduated in millibars. Readings of the 'Attached Thermometer' ceased with effect from 1 December 1948. For December 1948, MSL values were prepared taking the Att Therm value as the average for December for the previous 10 years 1938–47 and using the calculation as set out in section 3.3. From January to August 1949, the MSL correction is given in the observations register, and the MSLP has been taken as the As Read +MSL correction.

4.3.2 | September 1949 to December 1960: Fortin Barometer

The Browning Fortin barometer was re-introduced on 1 September 1949, and aside from the six months 28 August 1957 to 28 February 1958, when it was away for cleaning once more, it remained in use until barometric pressure observations were discontinued after 31 December 1960. The barometer was re-certified by Negretti & Zambra (certificate dated 5 February 1958), with errors no more than 0.4 hPa at any point within the calibration range. The August 1958 inspection report states that a handful of comparisons of Durham's MSL pressure against neighbouring synoptic stations around the date of the

TABLE 4 Details of the twice-daily Durham Observatory digital pressure series 1843–1960

Column header	Cell contents
YYYY MM DD	Date as YYYY MM DD character string (two entries per day)
YYYY MM DD HHmm	Date and time as YYYY MM DD HHmm character string (one entry per observation)
DD	Date in month (1–31)
MM	Month (1–12)
YYYY	Year (1843–1960)
HHmm	Observation hour HHmm—mostly 0,900 or 2,100, GMT from Oct 1885
Missing	Flag: Barometer 'As Read' reading missing = 1, else 0 or blank
AsRead_inHg	Barometer 'As Read' in inches of mercury (inHg) to November 1948, blank thereafter. This is the barometer reading as observed and digitized and includes numerous errors
AsRead_hPa	Barometer 'As Read' in millibars (mbar or hPa) throughout—inHg converted by x 33.86388. This is the barometer reading as observed and digitized and includes numerous errors
AttTherm_C	Barometer 'Attached Thermometer' in degrees Celsius—converted from °F as necessary. The record runs from July 1843 to November 1948 only
SLP_hPa	Station level pressure—barometer 'As Read' reduced to 0°C using the Attached Thermometer reading (see text for details), to December 1948 only
Tdry_C	Observed external air temperature (dry bulb in screen) in degrees Celsius. Some are missing; estimates were made using neighbouring values or, occasionally, monthly means over several years
MSLP_RAW_hPa	Calculated MSL pressure in millibars (hPa). MSL calculation details are given in the text. This is the RAW value, prior to quality control. Between 1843 and 1948, this is calculated from the observed As Read and Attached Thermometer with dry bulb temperature, as explained in the text; from 1949 to 1960, this is the As Read +MSL correction as given in the digitized observations register
MSLP_QC_hPa	Calculated MSL pressure in millibars (hPa). This is the CORRECTED value, post-quality control (see text for QC details), based upon the SLP_hPa value 1843–1948, or the As Read +MSL correction 1949–60
MSLP_QC_gapfilled_hPa	This is identical to MSLP_QC_hPa except that gaps are filled using the 20CRv3 ensemble mean gridpoint value +0.5 hPa to provide an unbroken series
MSLP_20CRv3_hPa	20CRv3 ensemble mean (hPa) for the nearest gridpoint value (55°N, 2°W) for the closest 3 h interval to the observation time. See text for sources. On average, this is about 0.5 hPa lower than the value expected in Durham as a result of the climatological decrease in pressure northwards, but obviously this will vary with pressure gradient and isobar orientation.

TABLE 5 Monthly and annual averages of MSL pressure at Durham Observatory, average of 0900 and 2100 GMT observations, various periods 1851–80 to 1931–60. Units—hPa less 1000.

Period	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	Year
1851–80	10.8	13.5	12.7	14.6	15.2	14.5	13.8	13.4	13.7	11.2	12.9	12.0	13.17
1861–90	12.4	13.8	12.2	14.0	15.4	15.6	13.3	13.2	13.5	12.0	11.4	12.4	13.24
1871–1900	13.7	14.1	12.7	13.5	15.7	15.6	13.3	12.9	14.1	11.9	12.0	11.6	13.41
1881–1910	14.5	14.0	11.8	13.5	15.6	16.5	14.1	12.9	15.9	12.2	12.6	10.9	13.70
1891–1920	13.9	12.5	10.6	13.8	16.1	16.2	14.9	13.1	16.1	12.3	12.7	9.2	13.43
1901–30	12.9	12.2	11.4	12.8	15.2	15.9	14.4	12.6	16.0	12.3	11.6	9.4	13.06
1911–40	11.6	13.1	12.2	13.0	15.5	15.6	13.3	13.5	14.9	12.1	10.6	10.7	12.99
1921–50	11.7	13.9	14.8	13.0	15.3	15.4	13.0	13.3	14.4	12.6	10.9	12.2	13.36
1931–60	11.9	13.7	14.8	14.7	16.4	15.4	13.1	13.4	14.4	13.5	11.5	11.1	13.68

inspection indicated that the barometer read up to 1.9 hPa too *low*, although the average of the observatory's 0900 GMT readings for that month compared with nearby sites would suggest that the error was about 1.0 hPa too *high* at that time.

4.3.3 | 28 August 1957 to 28 February 1958: Aneroid Barometer

Daily observations were made with a temperature-compensated aneroid barometer loaned by the Met Office for this six-month period (note on site file dated 28 October 1957). This type of instrument does not require temperature correction and thus no 'Attached Thermometer' readings are available for this period.

This instrument appears to have read 27–28 hPa too low—possibly as a result of the MSL adjustment being incorrectly set—but otherwise appears to have indicated daily pressure changes accurately and reliably. During this period, the MSLP was taken as As Read +27.5 hPa. Two observations during this period required additional corrections for probable 10 mbar reading errors.

5 | THE DURHAM OBSERVATORY DIGITAL PRESSURE RECORD

The entire Durham twice-daily pressure series 1843–1960 is available on the University of Reading Research Data Archive at http://dx.doi.org/10.17864/1947.328 as an open access dataset under a Creative Commons Attribution 4.0 International Licence. The file format is Comma Separated Variable (.csv), and the file size is 8 MB. The contents of the file are listed in Table 4, and as a ReadMe file within the same location.

Three options are available for the Durham MSLP series—the 'raw' (as observed) record, including gaps where they occur; the corrected (post QC) record, including gaps; and a corrected (post QC) record, where gaps have been filled using the 20CRv3 gridpoint data +0.5 mbar to provide an unbroken series. Gaps in the record amount to 1.3% of the record (Table 3) and corrections to 0.42%, distributed fairly evenly throughout the record.

Missing data are shown blank (empty cell), but note that there are no missing cells in the date/time headers, for the 20CRv3 ensemble mean gridpoint values or for the gapfilled pressure series.

6 | RECORD SUMMARY

6.1 | Monthly and annual averages

Table 5 sets out monthly and annual averages of MSLP at Durham over various 30 year periods. These averages are of the *corrected* series, with gaps filled by 20CRv3 gridpoint values +0.5 hPa where necessary. Values are shown minus 1000 hPa.

6.2 | Extremes on record

6.2.1 | Daily extremes

Table 6 lists the highest and lowest barometric pressure recorded at Durham Observatory by month (with date and time) and by year, from the *corrected* series (none of these records are from gap-filled missing data). It should be noted that as readings were taken only twice per day,

TABLE 6 Monthly and annual extremes of MSL pressure at Durham Observatory, in rank order, from morning and evening observations only (usually 0900 and 2100 GMT), period July 1843 to December 1960. Units—hPa, omitting initial digit (i.e. 10 for the maximum values, and 9 for the minimum).

Period	J	F	M	A	M	J	J	A	S	O	N	D	Year
Maximum	52.5	48.2	44.9	42.5	42.3	40.7	37.7	35.0	39.3	40.5	42.9	47.4	52.5
Year	1907	1902	1935	1906	1881	1959	1911	1874	1851	1956	1922	1926	1907
Date	23	1	9	8	10	13	10	20	16	31	15	23	23 Jan
Hour	09	09	09	21[a]	10	09	09	22	09	09[b]	09	21	09
Minimum	50.7	59.8	62.3	70.2	72.0	82.4	77.2	68.5	71.9	58.5	64.2	36.2	36.2
Year	1884	1951	1876	1948	1943	1938	1922	1917	1935	1959	1881	1886	1886
Date	26	5	10	1	8	28	6	28	17	27	27	8	8 Dec
Hour	22	09	10	09	21	21	09	09	09	09	10	21	21
Monthly pressure range	101.8	88.4	82.6	72.3	70.3	58.3	60.5	66.5	67.4	82.0	78.7	111.2	116.3

Note: [a] April highest value 1042.5 hPa equalled at 21h on 11 April 1938.

[b] October highest value 1040.5 hPa equalled at 09h on 23 October 1958.

TABLE 7 The ten highest and ten lowest barometric pressures on the Durham Observatory record 1843–1960, with the date and observation time, together with the 20CRv3 gridpoint ensemble mean for that date and time. Units hPa

Date	Time	Durham QC MSLP hPa	20CRv3 gridpoint ensemble mean hPa	Notes
Highest MSL pressures				
23 Jan 1907	0900	1052.5	1050.8	Slightly high; North Shields 1050.8 hPa at 0800 and 1049.1 hPa at 1800. True maximum probably between 1051 and 1051.5 hPa
31 Jan 1902	0900	1050.8	1047.8	
31 Jan 1902	2100	1050.7	1047.7	
22 Jan 1907	2100	1049.9	1047.5	
26 Jan 1932	0900	1049.7	1046.5	
9 Jan 1896	0900	1048.8	1047.1	'Raw' value 1051.2 hPa appears too high
26 Jan 1932	2100	1048.7	1045.1	
1 Feb 1902	0900	1048.2	1046.7	
23 Jan 1907	2100	1048.1	1047.1	
25 Jan 1932	2100	1047.7	1045.4	
Lowest MSL pressures				
8 Dec 1886	2100	936.2	952.8	Reanalysis in error—depth and timing
26 Jan 1884	2200	950.7	945.1	Reanalysis system speed too slow
9 Dec 1886	0900	953.7	958.3	
3 Dec 1909	0900	954.7	954.2	
4 Feb 1951	2100	955.4	954.3	
1 Jan 1949	2100	955.7	956.3	
8 Dec 1886	0900	956.3	973.1	
4 Feb 1951	2100	956.4	954.3	
6 Dec 1847	2100	956.9	965.8	Minimum noted as 956.8 hPa at 2025 common time
19 Feb 1900	2100	957.0	962.5	
1 Jan 1949	0900	957.7	957.1	

TABLE 8 Highest and lowest monthly mean MSL pressure (hPa) at Durham Observatory, and the extreme range in monthly means, over the period of 1843–1960

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	Year
Maximum	27.4	**34.6**	29.4	27.0	25.8	24.1	21.8	22.2	24.7	22.2	26.2	24.8	17.0
Year	1880	1932	1953	1938	1896	1865	1955	1947	1865	1947	1867	1926	1921
Anomaly (+)	15.5	20.9	14.6	12.3	9.4	8.7	8.7	8.8	10.3	8.7	14.7	13.7	3.3
Minimum	**94.5**	98.8	97.6	05.1	07.7	04.9	05.1	03.4	03.6	00.0	99.4	97.0	07.9
Year	1948	1937	1876	1920	1925	1852	1861	1860	1918	1903	1877	1868	1872
Anomaly (−)	17.4	14.9	17.2	9.6	8.7	10.5	8.0	10.0	10.8	13.5	12.1	14.1	5.8
Monthly range	32.9	35.8	31.8	21.9	18.1	19.3	16.7	18.8	21.1	22.2	26.8	27.8	9.1

Note: The monthly mean is the average of the morning and evening observations (usually 0900 and 2100 GMT). Anomaly from 1931 to 1960 normal also stated. Values omit initial digit (i.e. 10 for values >1000 hPa, and 9 < 1000 hPa). Highest and lowest values shown in **bold**.

these are almost certainly under-estimates of the range of barometric pressure at the site, since extremes may occur at any hour of the day.

The ten highest and ten lowest MSL pressure readings at Durham over the period 1843–1960 are listed in Table 7, together with the equivalent 20CRv3 gridpoint ensemble mean value closest to that observation time.

Details of the circumstances of many of the events listed in Table 7, together with synoptic descriptions, can be found in Burt (2007a, 2007b).

6.2.2 | Monthly and annual extremes

Table 8 lists the highest and lowest monthly barometric pressure means recorded at Durham Observatory, using the *corrected* series including any gap-fills from 20CRv3 as necessary. The anomaly from the 1931–60 monthly average (from Table 5) is also shown for each entry. The highest monthly mean pressure on the Durham record was in February 1932, when the mean was 1034.6 hPa; only two other months have averaged higher than 1030 hPa, namely February 1959 (1030.4 hPa) and February 1891 (1030.3 hPa); not surprisingly, all three months were very dry in Durham. The lowest monthly mean pressure on the record was in January 1948, when the mean was 994.5 hPa. Other notably cyclonic months include the Decembers of 1868 and 1959, with a monthly mean of 997.0 hPa.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at http://dx.doi.org/10.17864/1947.328. Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tvyxz/wiki.

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