



Digitization of Historical Atmospheric Electricity Records from Lerwick Observatory (1927–1956) using Citizen Science

Hripsime Mkrtchyan¹, Keri A. Nicoll¹, R. Giles Harrison¹, Anna Hovhannisyan²

¹ Department of Meteorology, University of Reading, UK

² Yerevan State University, Armenia

Corresponding author: Hripsime Mkrtchyan, email: h.mkrtyan@reading.ac.uk

Abstract. Measurements of the atmospheric electric field, measured as the potential gradient (PG), were carried out at Lerwick Observatory (Shetland Isles, UK) during the twentieth century and provide a unique resource for studying links between atmospheric electricity, the global electric circuit (GEC), and climate variability. Most of these historical observations existed previously only as handwritten or printed records, limiting their accessibility for modern analysis. A comprehensive digitization of the Lerwick PG handwritten records from 1927–1956 has been undertaken using a citizen science approach, through the Zooniverse platform. The resulting ready-to-use dataset provides a quality-controlled record of hourly potential gradient measurements, enabling new investigations into long-term atmospheric electricity variability, the global electric circuit, and their associated connections to climate. In addition, seasonal variability analysed on an hourly basis across the entire observation period is presented for the first time. The dataset is available at Zenodo under <https://doi.org/10.5281/zenodo.23427164> (Mkrtchyan et al., 2026).

1. Introduction

Earth has a “Global Electric Circuit” (GEC) (Rycroft and Harrison, 2012) through which thunderstorm charge separation sustains the large-scale electric current circulating globally in the atmosphere. Disturbed weather regions (thunderstorms and shower clouds) act as energizers in the global electric circuit (Wilson, 1921, 1929; Williams, 2005, 2009). Hence, the GEC is a fundamental coupling network of the climate system connecting electrically disturbed weather regions with fair weather regions across the planet (Nicoll et al., 2019). Furthermore, as lightning is now recognised as an Essential Climate Variable (ECV, Aich et al., 2018), lightning-related atmospheric electricity parameters have assumed correspondingly greater importance. Long-term measurements of the atmospheric electric field (or Potential Gradient (PG), as it is also known), may consequently provide a valuable resource for investigations of long-term variability in lightning-related climate processes and the response of the GEC to climate change.

The PG in fair-weather is a GEC variable which is present globally and can be recorded near the surface using durable instrumentation. Unlike lightning or magnetic fields, fair-weather PG cannot be measured remotely (Nicoll et al., 2019). The GEC diurnal variation in PG, known as the Carnegie curve, has a maximum around 19 UT and a minimum around 03UT. This diurnal variation is related to the diurnal variation in global thunderstorm activity (Whipple, 1929, Whipple and Scrase, 1936) is a fundamental characteristic of the GEC and plays an important role in its understanding (Harrison, 2013).

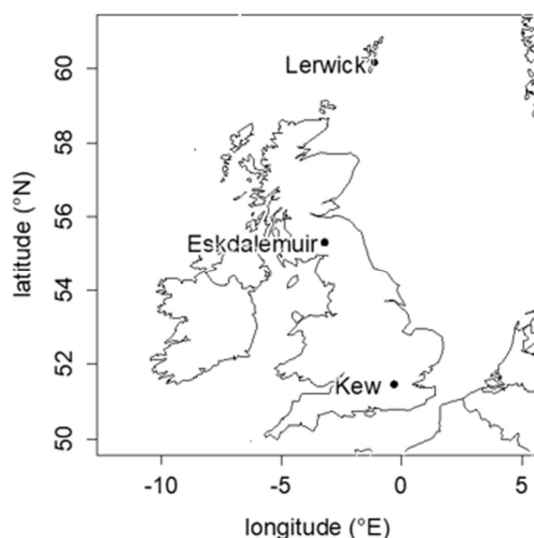
The UK has a long history of atmospheric electricity research, carried out effectively at the geophysical observatories of Kew (near London), Eskdalemuir (southern Scotland), and especially at Lerwick (Shetland), see Figure 1 (Harrison, 2003). This publication focuses on measurements from Lerwick Observatory, which is located about 2 km from Lerwick town centre, at 80 m above sea level. A consistent and well-regulated long-term PG record was obtained at that site by the Met Office, between 1925 and 1984. A full historical description of the Lerwick atmospheric electricity measurements has been



provided by Harrison and Riddick, 2022 (hereafter HR22). In addition to the atmospheric measurements, hourly meteorological observations at Lerwick are available from 1923. These provide important corroborating information for interpreting PG measurements, as PG is a highly variable parameter, influenced by local meteorological conditions such as precipitation, fog, and low cloud, as well as by aerosol (Harrison and Carslaw, 2003), and ionisation changes such as from space weather (e.g. Kleimenova et al., 2018). Variability in PG at a local site can also reflect changes in the GEC, meaning that even surface measurements from a single site can provide GEC information. PG measurements recorded at Lerwick have previously been compared with the Carnegie curve, particularly with measurements obtained during the final voyage of the Carnegie on 1st December 1928 (HR22). The comparison showed good agreement between the simultaneous observations made at Lerwick and those recorded aboard the Carnegie. Therefore, for climate-related atmospheric electricity research, the PG measurements at Lerwick are likely to be especially valuable, particularly since the island location of the site means that it has minimal interference from aerosol pollution (HR22).

The records obtained at Lerwick were originally published annually by the Met Office in The Observatories' Yearbook (hereafter OYB). After the OYB's cessation (last volume published in 1967), the later data values were kept in unpublished observatory summary records, as described in Harrison et al., 2023. For long-term preservation purposes, the summary sheets were scanned by the Hadley Centre of the Met Office in 2003. However, this scanning process created only images, and the data values were not transcribed into a computer-readable format (Mkrtchyan et al., 2024; Harrison et al., 2025), and hence not amenable to modern analysis. Previously published studies using the Lerwick PG have therefore relied on selected subsets of this dataset, including monthly mean values and limited hourly measurements for specific periods (e.g. Hamilton 1965, Harrison et al. 2003, 2011, 2022). A recent study by Slyunyaev et al., 2025 (a,b) demonstrated the scientific importance of the Lerwick dataset for investigations linking monthly mean values of PG and limited hourly measurements for specific periods to investigate seasonality in the GEC. Until now, however, much of the historical PG record has remained accessible only as handwritten or printed observation sheets.

This study presents the first attempt to digitize the complete handwritten portion of these historical handwritten PG measurements at hourly resolution from Lerwick Observatory from 1927 to 1956 using the Zooniverse citizen science platform. The Zooniverse citizen science platform (Simpson et al., 2014) is an online environment that enables researchers to design projects in which volunteers contribute to tasks, such as data classification and transcription. Citizen science has a long history in atmospheric research and has recently gained renewed attention, providing effective opportunities for large-scale data collection through public participation. Bonney et al. 2009 demonstrated that citizen science is particularly valuable for projects involving large temporal datasets, where public participation can support complex scientific investigations and large-scale data processing. Successful citizen science relies on recognising volunteers as collaborators (Krukowski et al., 2022; Frissell et al., 2023) with diverse expertise, and by providing appropriate training and mentorship to use their skills effectively (Grandin et al., 2025). Many previous citizen science projects have demonstrated the effectiveness of public participation for large-scale atmospheric and environmental research. For example, projects such as the NASA "Clouds Around the World" initiative (Robles et al., 2020), and the National Eclipse Weather Experiment (NEWEx) (Barnard et al., 2016) successfully used citizen scientists to collect extensive meteorological observations while also supporting broad public engagement. The design and implementation of this Zooniverse project followed key principles outlined by Bonney et al., 2014, including project design, volunteer recruitment and training, data validation, and dissemination of results.



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78

79 **Figure 1. a) Locations of observatories on the map, b) Lerwick observatory (Lat 60.139 Lon -1.183, 82 m amsl), adapted from**
 80 **HR22**

81 In this work, we describe the resulting dataset which has been recovered. This dataset is valuable for a range of scientific
 82 applications, particularly for the study of the GEC and its connection to climate variability (HR22). A positive relationship
 83 was found between December PG variations measured at Lerwick and sea surface temperature anomalies in the Niño 3.4
 84 region during the period 1968–1983(Harrison et al. (2011, 2022)). This demonstrates that PG data can contain climate
 85 information and that historical PG measurements can be used not only to study GEC variability, but also to support SST
 86 reconstructions for periods with uncertain ENSO records.

87 The paper’s structure is as follows: Section 2 describes the Lerwick PG observations and the historical record sheets for
 88 the two observation periods (1927–1945 and 1946–1956). Section 3 presents the digitization methodology, including the
 89 Zooniverse citizen science platform and the workflows developed for each period. Section 4 describes the processing and
 90 quality control of the transcribed values. Section 5 presents the resulting dataset, its variables, calibration factors, and its
 91 time-series, diurnal, seasonal, and annual characteristics. Section 6 assesses the validation of the dataset against
 92 independent reference data and discusses known limitations and data quality variations. Finally, Section 7 concludes the
 93 work with the main findings and comments on the scientific value of the digitized dataset.



2. Observations of the Potential Gradient

The PG is the voltage difference between a flat region of the Earth's surface (normally taken as ground potential (i.e. 0 V) and a point at a certain height vertically above it. In fair weather, the typical PG at 1 m above the surface is approximately +150 V/m, depending on the conductivity of the local air, and can be measured using a suitable sensing electrode and an electrostatic voltmeter. At Lerwick, a radioactive potential probe was used as the sensing electrode. It was connected to an electrometer and chart recorder so that continuous recordings could be made. This system of recording equipment was known as an "electrograph".

A Benndorf electrograph was used from 1925-1960 and Brewer electrograph thereafter, with values read from chart recorder traces (a detailed description can be found in Harper, 1950; HR22). The electrograph and chart recorder had a full-scale range of $\pm 2,000$ V/m. Insulation and scale tests of the system were made daily with a Wulf electrometer by reducing the actual hourly measured values to absolute values after comparing them against external observations made with the Wulf electrometer and a stretched wire potential equaliser (Harper, 1950). A summary of major events in the operation of the Lerwick atmospheric electricity apparatus is presented in Table 1 of HR22, which details instrument installation and relocation, calibration and performance testing, collector modifications, maintenance and repair activities, instrument upgrades, and the introduction of later related atmospheric electricity measurements of the air-earth current. These changes provide important context for interpreting long-term variability in the PG record and identifying periods affected by equipment issues.

2.1 Examples of the historical record sheets

The historical PG observations from Lerwick Observatory were originally recorded on structured paper sheets containing daily summaries of measurements at hourly resolution. As mentioned in HR22, the hourly mean PG values were from 60 min periods centred at the exact hour (GMT) up until 1931, and on the half-hour in the records thereafter. Each sheet includes date information. In some cases, a single sheet contains records for more than one month, requiring careful identification of the temporal boundaries within the document. The sheets also include a classification of day types, which reflects the prevailing atmospheric conditions.

The day type classification is based on earlier practices in magnetic observations, where each day was succinctly described according to its overall level of disturbance. For this, a number representing the character of the chart trace was assigned to each day: (0) indicates no negative PG values, (1) indicates negative PG values lasting less than 3 hours, and (2) indicates negative PG values lasting more than 3 hours. From 1927 onward, additional letters were introduced to describe the amplitude of PG variations within the day. The letter (a) indicates that PG values remained below 1000 V/m, (b) indicates that PG exceeded 1000 V/m occasionally, and (c) indicates that PG exceeded 1000 V/m frequently (HR22). Disturbed weather conditions are more likely to result in larger PG values, and precipitation often causes negative PG, therefore, day type 1 and 2 are most likely non-fair-weather conditions (for the entire digitized period). It is important to note that day type 0a does not necessarily denote fair weather conditions – only that the PG was positive and less than 1000 V/m.

The historical record sheets exhibit two distinct structural formats, corresponding to different periods: the first format covers the years 1927–1945, and the second for the period 1946–1956. For clarity, the digitization methodology is described separately for these two distinct periods, hereafter referred to as Period 1 (1927–1945) and Period 2 (1946–1956). These differences affect the arrangement of the recorded information, which is important to consider for data transcription via citizen science methods, including the placement of the month, day type classification, day numbers, and hourly PG measurements.



134 2.1.1 Period 1: Record sheet structure 1927-1945

135 In Period 1 each sheet (Met Office form number 3745), typically contains up to 31 days of observations with 24 hourly
 136 measurements per day. Figure 2 shows an example of sheets from the 1927–1945 period. The record sheets for this period
 137 include an “element” section to be entered manually, which indicates their origin as general-purpose autographic recording
 138 sheets. For the Lerwick data used in this study, this field is individually completed by hand as “Potential Gradient” (PG).
 139 The sheets also include year, observatory name, month, and day type classification. However, in some cases, a single sheet
 140 contained data for more than one month or more than one day type, which requires careful interpretation during digitization.
 141 In these cases, volunteers were provided with detailed guidance within the Zooniverse workflow on how to identify the
 142 correct month and day type and to digitize each data block separately (see Section 3).

143
 144 **Figure 2. Period 1 example of a historical handwritten observation sheet of potential gradient (PG) for October–November**
 145 **1933. Two different months are shown (one above the other). The year and the first month and the day type classification**
 146 **(e.g., 0a for fair weather and 1a or 2a for disturbed weather) are indicated at the top of the sheet. The measurements of the**
 147 **second month along with its name, are posted in the middle of the sheet, just after the summary rows of the first month. Each**
 148 **day’s values are provided in rows, while hourly PG observations are arranged as 24 columns. Statistical summary rows (e.g.,**
 149 **sum, stv) are also present on the sheet but were excluded from the digitization process. (Source: Met Office Archive, Lerwick**
 150 **Observatory hourly potential gradient record sheet, October–November 1933)**

151 As illustrated in Figure 2, the day type classification is typically indicated at the top of the sheet together with the year and
 152 month. However, this layout is not consistent across all records. In some cases, when more than one day type was observed
 153 within the same month, an additional day type label was inserted within the table itself, usually in the middle of the sheet.
 154 The measurements corresponding to the new day type then continue directly below this information, forming a separate
 155 block of records for the same month. After each block there are summary rows (e.g., Summary (sum), non-cyclic change
 156 (“ncc”, i.e. baseline drift), standard deviation value (stv)), which provide basic auditing information. The observers used
 157 these values for data checking and reporting purposes. Since they do not correspond to direct observations and could in



158 principle be regenerated, they were excluded from the digitized dataset and the volunteers instructed to ignore these rows
 159 during transcription.

160 The variation in the sheet structure was explicitly addressed by using the flexibility possible in the Zooniverse digitization
 161 workflow, where volunteers were instructed to identify the relevant month and day type before entering the corresponding
 162 data. The workflow guided participants to digitize each block of records separately, reducing the risk of measurements
 163 being assigned to an incorrect month and day type classification.

164

165 **2.1.2 Period 2: Record sheet structure 1946-1956**

166 An example of the sheet structure for Period 2 is shown in Figure 3, which is noticeably different from the structure used
 167 in Period 1 (Figure 2). The historical observation sheets differ not only in their structural layout but also in the availability
 168 and organization of the recorded measurements, as well as the content (e.g. additional information on the “multiplier” used
 169 to convert from the raw electrograph “deflexion” values to final PG is included). While the Period 1 format typically
 170 presents daily records with a consistent structure of hourly PG observations, the Period 2 format used from 1946 onward
 171 (Figure 3) follows a different tabular arrangement and records data on a weekly basis, with each sheet representing
 172 approximately one week of observations. In this format, days are arranged as columns and hourly observation times are
 173 listed as rows, but the availability of measurements within a day is not always complete. In some cases, the full 24 hours
 174 of observations are available, while in others only a limited number of measurements are recorded. For example,
 175 observations were often made at six-hourly intervals rather than at full hourly resolution, resulting in reduced daily data
 176 coverage.

177 From 1946-1956, the PG was recorded in a purpose-designed format (mentioned in top-left, form 3520), with a column
 178 specifically headed “Gradient in Open”, together with related information such as date, hour, day type classification,
 179 multiplier (a scaling factor) and observatory name. It should be noted that the multiplier is only present in Period 2 (1946–
 180 1956) and was not recorded in Period 1 (1927–1945). Furthermore, the sheets include additional parameters beyond PG
 181 values, such as electrograph deflexion distance and the duration of negative potential. During digitization, the primary
 182 focus was on extracting the final PG measurements. When PG values were not available, the deflexion values were
 183 digitized instead. Those values were combined with the corresponding multiplier to calculate PG. The column indicating
 184 the duration of negative potential was not transcribed.

185 Consequently, two separate digitization workflows for Period 1 and Period 2 were developed within the Zooniverse
 186 platform to accommodate these structural variations and to ensure consistent and accurate transcription of the observations
 187 for each period. The digitization procedures for each of these formats are described in the next section.



Form 3520. Instruction to Tabulator—Use the other side of the sheet first.

Tabulated Hourly Values of the Electrogram,
at Lerwick, for February, 1946. Tabn. No. 8

Hour	DAY 18	DAY 19	DAY 20	DAY 21	DAY 22	DAY 23	DAY 24	
	Volts per mm.		Volts per mm.		Volts per mm.		Volts per mm.	
	38.5		38.6		38.9		39.0	
	1a		1c		1c		1c	
	1a		1c		1c		1c	
1	2.3	89	1.3	50				
2	2.1	86			0.19			0.18
3	2.0	77	1.1	46	2.5	7.7	0.3	0.2
4	2.0	77			0.1			0.2
5	1.8	69			0.8			0.5
6	2.1	81			0.18			0.19
7	2.0	77			0.10			0.18
8	2.3	89			0.20			0.3
9	3.0	116	2.7	100	2.5	7.7	0.3	0.2
10	3.0	116			0.19			0.4
11	2.4	92			0.13			0.4
12	2.3	86			0.5			0.4
13	2.9	112			0.11			0.4
14	3.5	132			0.16			0.4
15	3.2	125	8.0	300	4.0	154	4.8	187
16	2.0	77			0.18			0.36
17	0.3	12						
18	1.0	39			0.4			
19	1.2	46			0.8			
20	4.2	162						
21	3.7	142	2.6	100	5.4	200	8.5	329
22	3.5	135			0.22			0.2
23	1.3	50						0.3
24	1.9	73						2.8
Sum	1 to 24	2159	0.12		2.19		3.01	2.41
Corr.	rected							
Sum	Daily							
Mean								

NOTES ON LARGE DISTURBANCES.

NOTES. I.—The "Multiplier" used for finding the Potential Gradients in volts per mm. from the Deflection in mm., is the product of the Instrumental Scale Value and the Exposure Factor.
II.—Values refer to periods of 60 minutes centering at the exact hours G.M.T.
III.—The cause of any omission of the hourly values is to be stated in the "Remarks." Any interference with the instrument is to be carefully noted on the Curves.

REMARKS.

Curves read by W.D.
Readings checked by W.D.
Arithmetic by W.D.
checked by W.D.

(Turn over.)

188

189 **Figure 3.** Period 2 example of a historical observation sheet of PG for February 1946 recorded at Lerwick Observatory. In this
190 sheet the measurements for individual days of the month are arranged as columns, while hourly observation times are listed as
191 rows. The day number, multiplier, and day type classification (e.g., 1a, 1c, 2c) are indicated at the top of each daily column.
192 The table contains handwritten values corresponding to the electrogram readings and derived PG measurements. Additional
193 rows near the bottom of the sheet contain summary information, which were not included in the digitization of the hourly
194 measurements. (Source: Met Office Archive, Lerwick Observatory hourly potential gradient record sheet, February 1946)

195 3. Digitization Methodology

196 Digitization of the UK historical atmospheric electricity data presents significant technical challenges. This was due to the
197 age of the original data sheets, as physical degradation and ink bleeding across table cells make some records difficult to
198 read reliably, even for the human eye. This section describes the methodology in which the data transcription tasks take
199 place through the online Zooniverse interface.



200 3.1.1 Citizen Science Platform Zooniverse

201 To create a project on the Zooniverse citizen science platform, researchers must first register an account and then design
 202 the workflow using the project-building interface. In this study, a workflow refers to the structured sequence of tasks that
 203 volunteers follow to digitize the data. Although the platform provides a limited set of built-in tools, complex workflows
 204 can be developed by combining these tools through logical task sequences. The Zooniverse platform also provides detailed
 205 guidelines and documentation to assist project developers throughout the design process. Before public release, projects
 206 typically undergo a beta testing phase, during which the workflow is shared internally with experienced Zooniverse
 207 volunteers who provide feedback on usability and task clarity. This feedback allows researchers to improve the workflow
 208 before the project is officially launched. Once finalized, the project – “Atmospheric Electricity for Climate (AtmosEleC)”
 209 was published on the platform with the support of the Zooniverse team, who assist in promoting projects to the broader
 210 volunteer community. Initial analysis of project participation showed a strong link between media engagement activities
 211 and an increase in the number of volunteers, as previously identified in other citizen science projects (Grandin et al., 2025).
 212 This highlighted the importance of continued engagement efforts to sustain volunteer interest over the duration of the
 213 project. This employed a range of approaches including posters, media outreach, and university blog posts, to maintain
 214 volunteer participation. In particular, media opportunities played an important role in maintaining the project’s public
 215 profile and encouraging wider volunteer participation, including articles on the *University website*¹, *Meteorology*
 216 *department blog post*², *The Guardian*³ and *The Conversation*⁴, as well as BBC local radio interviews such as with Good
 217 Evening Shetland.

218 3.1.2 Detail of the digitization

219 Figure 4 shows a diagram of the workflow which was used for the digitization of the PG dataset. The complete digitization
 220 workflow consisted of five main stages. Those stages are:

- 221 1. pre-processing
- 222 2. Zooniverse workflow design
- 223 3. Zooniverse campaign
- 224 4. extraction of volunteer classifications
- 225 5. data processing and cleaning
- 226 6. final manual verification

227 This same workflow process was used for digitizing Period 1 and 2 separately due to the different nature of the sheet
 228 structure between these periods.

229 In the pre-processing stage the scanned handwritten sheets were standardised by cropping, resizing, and converting image
 230 formats to ensure compatibility with the Zooniverse platform. In some cases, images were also converted to grayscale to
 231 improve clarity. The Zooniverse workflows were designed for each period mentioned above separately using a limited
 232 available set of tools on the platform. This includes choosing task type, designing the task and preparing the instructions
 233 that guide volunteers in performing the task.

234 Following initial workflow creation, preliminary testing was carried out by a small number of volunteers (known as the
 235 beta testing phase in Zooniverse). Feedback from the beta volunteers helped to refine the workflow steps, and the main

¹ <https://www.reading.ac.uk/news/2024/Research-News/Explosions-captured-in-old-weather-data-that-needs-decoding>

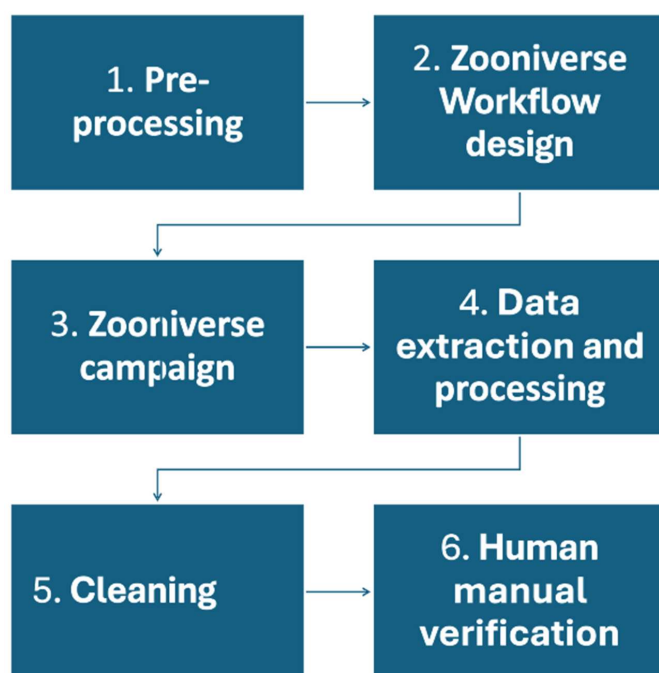
² <https://blogs.reading.ac.uk/weather-and-climate-at-reading/2024/atmospheric-electricity-for-climate-project-is-on-zooniverse/>

³ <https://www.theguardian.com/environment/article/2024/jun/06/el-nino-thunderstorms-lerwick-shetland-records-weatherwatch>

⁴ <https://theconversation.com/why-were-hunting-through-a-century-of-data-from-britains-northernmost-observatory-231471>



236 digitisation campaign was launched following this. For this, the prepared dataset was made available to volunteers who
 237 follow the workflow instructions by completing the assigned tasks. A key consideration in any Zooniverse project is to
 238 specify the number of times each sheet will be independently digitized. This quantity is known as the retirement number,
 239 which defines how many independent classifications of the same sheet are required for the task to be considered complete.
 240 Inconsistencies in digitisation by human keying of data are inevitable, therefore if the retirement number is too small, many
 241 erroneous values are likely, but if it is too large, the time taken to complete the digitisation process will be substantial with
 242 negligible benefit.
 243 Five attempts were originally specified as the retirement value, to balance data quality and processing time; however, the
 244 first version of the workflow for the Period 1 data required 112 days to complete for 285 sheets, indicating the need for a
 245 more efficient approach. Based on this experience, the retirement number was reduced to four for Period 2, which proved
 246 sufficient in allowing faster completion of the workflow (see Table 1 below, which summarises the characteristics of the
 247 digitisation).
 248 Following completion of the digitisation campaign, the values entered were extracted from the Zooniverse platform for
 249 further analysis. This included aggregating volunteer responses and filtering out unreliable entries to produce a refined
 250 dataset. The processed data were then subjected to a two-step cleaning procedure based on interquartile range (IQR) for
 251 each input (see section 4 for details).



252

253 **Figure 4. Workflow used for the digitization of historical atmospheric electricity records from Lerwick Observatory using the**
 254 **Zooniverse citizen science platform.**

255 Finally, the processed results underwent random manual verification to sample the accuracy and reliability of the final
 256 outputs. This step served as a quality control mechanism, allowing uncertain cases to be reviewed and corrected before the
 257 data are used in subsequent analyses.



Table 1. Characteristics of the Zooniverse digitization for Period 1 and 2.

	Period 1	Period 2
Digitized sheets	285	598
Workflow duration	112 days	113 days
Classifications per sheet	5	4
Total sheets digitized	883	
Number of volunteers	~1800	

3.2 Digitization Workflow for 1927–1945 Records (Period 1)

In the workflow of Period 1, volunteers were asked to identify the month, and the day type indicated on the sheet and select the corresponding option within the interface. The day type classification followed the notation used in the original records, where “0a” denotes fair weather conditions, while “1a” and “2a” represent disturbed weather conditions. In some cases, the notation “1a and 2a” appears in the records; this was treated as a single day type classification during the digitization process. If no day type was explicitly indicated on the sheet, volunteers were instructed to record the entry as “NaN”, which was manually checked afterwards.

After identifying the relevant month, year, and day type, participants proceeded to digitize the day numbers associated with the selected record block. These values correspond to the days of the month and were entered as a sequence separated by semicolon delimiters. Volunteers were instructed to focus only on the rows containing daily entries and to ignore statistical summary rows (e.g., with words like sum, stv), which represent derived statistics, possibly containing mistakes rather than original observations. These quantities may ultimately be recalculated.

In the final step, volunteers transcribed the corresponding potential gradient (PG) values recorded for the specified observation times. The historical sheets present hourly measurements arranged in columns, and participants entered the PG values sequentially by reading down the column and separating individual entries with semicolons. When negative values were present in the records, the negative sign was preserved during transcription to ensure accurate representation of the original measurements.

The workflow was also designed to accommodate variations in sheet structure, such as cases where multiple months or multiple day types were recorded on the same sheet. In these cases, the interface guided participants through additional steps to ensure that each set of observations was digitized separately and correctly associated with the corresponding month and day type classification to ensure accurate digitization of the observational information.

3.3 Digitization Workflow for 1946–1956 Records (Period 2)

A separate digitization workflow was developed in the platform to accommodate Period 2 datasheets. In this workflow, volunteers were first asked to identify the day, month, and year associated with each record. Also, volunteers recorded the day character information (day type classification), which is indicated in the header of each daily column. The corresponding multiplier value, indicated near the day heading, was also recorded as it is required for converting the instrument readings into PG values.

The PG values were listed in the column labelled “Gradient in Open.”, (GiO). Volunteers transcribed the values corresponding to the available hourly observations for each day. Because the records in this format do not always contain a complete set of 24-hourly measurements, the workflow allowed participants to enter only the hours for which data were present. When the GiO column was empty, but values were recorded in the Deflexion column, these deflexion values were digitized instead, allowing later recovery of PG values.

This structured workflow enabled consistent extraction of the relevant information from the weekly tabulated sheets despite variations in data availability and sheet layout. To facilitate the digitization process and reduce the amount of data required



294 in a single task, the workflow was divided into several smaller transcription units. For the Period 1 sheet format, where
 295 each sheet contains many hourly PG observations, the transcription tasks were separated into eight workflows
 296 corresponding to different three-hour time intervals. Each workflow contained the same task structure but focused on a
 297 specific subset of hourly measurements, allowing volunteers to digitize smaller portions of the sheet at a time.
 298 For the Period 2 sheet format, a different approach was used due to the weekly structure of the tables. Separate workflows
 299 were created for individual days of the sheet, allowing volunteers to select the specific day they intended to digitize based
 300 on the layout of the record. This approach simplified the transcription process and helped ensure that the extracted
 301 observations were correctly associated with the corresponding day and measurement block.

302 **4. Processing of transcribed values**

303 **4.1 Data processing and aggregation**

304 The transcription tasks were completed by approximately 1800 volunteers (see Appendix A) participating through the
 305 Zooniverse platform, providing multiple independent transcriptions (see table 1 in section 3.1) for each measurement and
 306 enabling reliable aggregation of the digitized values.

307 After completion of the transcription tasks by Zooniverse volunteers, the resulting data were downloaded from the platform
 308 in CSV format. However, several columns contained the transcription outputs in JSON format (which is a standard format
 309 for Zooniverse output), requiring additional processing before analysis could be performed. The first step therefore
 310 involved extracting and converting the relevant JSON fields containing the digitized entries into a structured tabular format
 311 suitable for further processing.

312 Following this conversion to a consistent format, individual digitized files were generated for each image, as the raw export
 313 from Zooniverse stores all classifications within a single combined file. Each transcription task had a retirement limit of
 314 four to five classifications per sheet (see section 3.1.2 for details), meaning that each cell in the dataset could contain up
 315 to five independent volunteer entries, although in some cases fewer entries were available.

316 To extract a single value for each hourly measurement, an aggregation procedure was applied to the volunteer entries. For
 317 each value, the IQR was calculated to evaluate the spread of the transcribed values, and the final value adopted was
 318 determined by taking the mode of the values (i.e. the most common entry). In cases where no single mode existed — for
 319 example, when all volunteer entries differed or votes were evenly split — the measurement was manually checked and
 320 validated by the authors against the original record sheet to determine the best choice value. These values and their
 321 associated IQR statistics, to flag discrepancy when present, were stored in monthly data files.

322 During the processing stage, several additional corrections were performed. Obvious transcription errors such as misplaced
 323 semicolons, incorrect numbers of entries, and empty rows that could cause alignment errors, were manually corrected. For
 324 the Period 1 dataset, the recorded day contains a complete set of 24-hourly observations, and therefore missing data were
 325 not encountered. In contrast, the Period 2 records occasionally contain incomplete hourly observations. In these cases,
 326 missing values were represented using the placeholder value 9999.

327 **4.2 Quality control and validation approach**

328 After the aggregation and cleaning procedures, the processed monthly datasets were combined into yearly files. Internal
 329 validation of the digitized dataset relied on two complementary checks: (1) the multiple independent volunteer
 330 transcriptions obtained for each measurement (Section 3), used to compute the IQR as a measure of agreement between
 331 transcribers, and (2) a manual quality control step involving checking randomly selected values and reviewing
 332 measurements for which the calculated IQR differed from zero. A non-zero IQR typically indicated disagreement among
 333 volunteer transcriptions, or, an illegible entry. In addition, cross-check plots (histograms and time series) were used to



identify outliers and inconsistencies. External validation of the digitized record against independent reference data, together with a discussion of known limitations and data quality variations, is presented in Section 6.

5. Dataset description

The recovered dataset contains atmospheric Lerwick Potential Gradient (PG) data between 1927 and 1945, with some missing hours between 1946-1956. Some properties of the data are now briefly investigated on hourly to annual timescales. To characterize the dataset and demonstrate its consistency with characteristic atmospheric electricity behaviour, the following subsections examine the diurnal, seasonal, and annual structure of the digitized PG record.

5.1 Variables and calibration factors

Table 2 presents the variables included in the digitized dataset. The dataset contains the hourly PG, together with the corresponding date and observation time. Hourly PG values are calculated as a 60 min mean, centred around the observation time, which is recorded in hours. From 1932 onward, the observation time is recorded at 30 minutes past the hour, rather than on the hour (e.g. 00:30, 01:30, 02:30).

For Period 2, measurements are not always available for all hours of the day, as observations were sometimes recorded only at specific hours rather than continuously over a full 24-hour period. In addition, for both Periods 1 and 2, there are cases where entire days are missing from the records. These gaps reflect the original observational data and have been retained in the digitized dataset as ‘9999’.

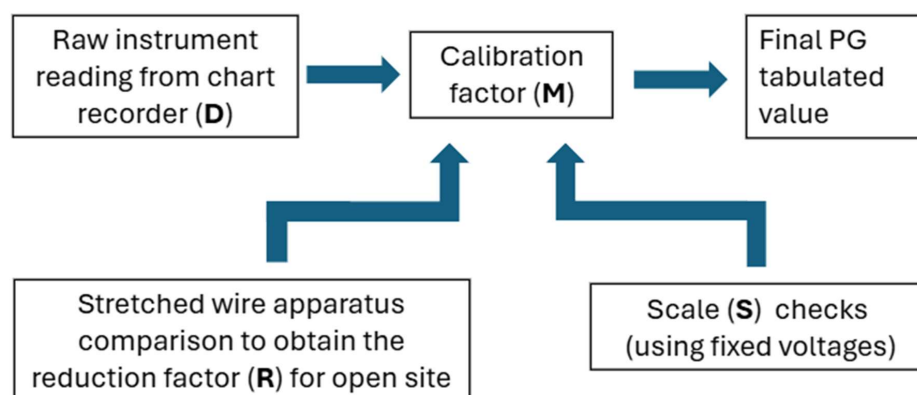
Table 2. Variables in the dataset

Variable	Description	Unit	Notes
PG	Potential gradient	V/m	
Date	Observation date	YYYY-MM-DD	
Hour	Observation time	hour	The observation times were offset by 30 minutes (e.g., 00:30, 01:30, 02:30) starting from 1932
Day type	Weather classification	code	
Multiplier	Multiplier	number	Only for 1946-1956

The dataset also includes the day type classification, which describes the weather conditions. For Period 2, an additional calibration factor, the “multiplier”, M , is provided, for converting instrument readings into PG values. M was used as a conversion factor, with the open site PG calculated as:

$$PG = D \times M \quad (1)$$

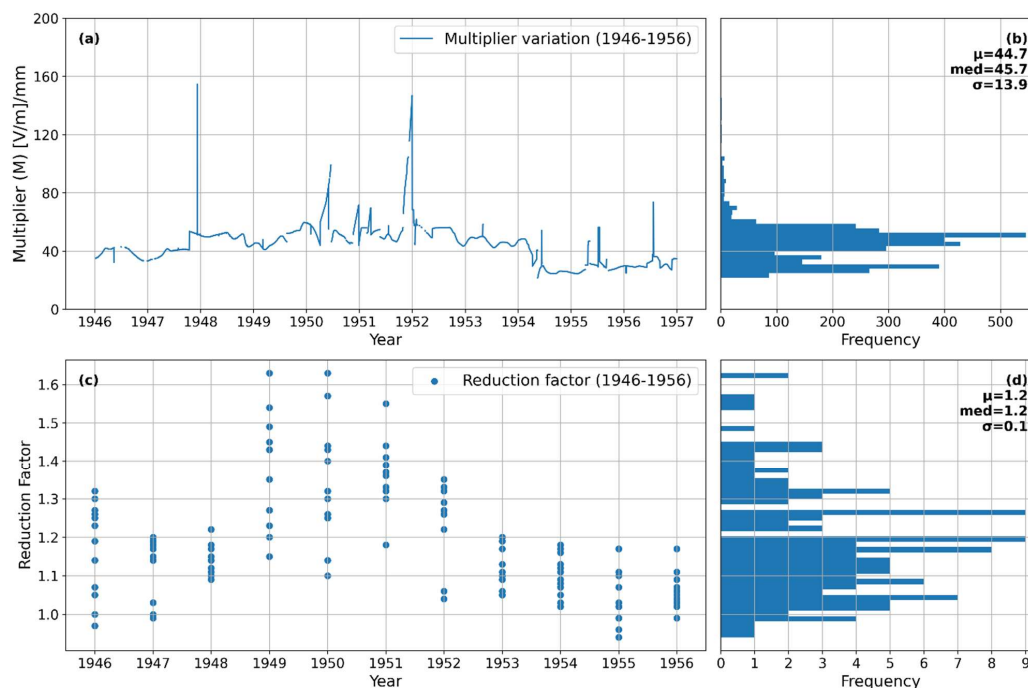
where D is the observed chart deflexion. M combines the geometrical reduction factor for the site (~ 1.3) and the chart recorder scale sensitivity, separately determined by using fixed reference voltages.



358

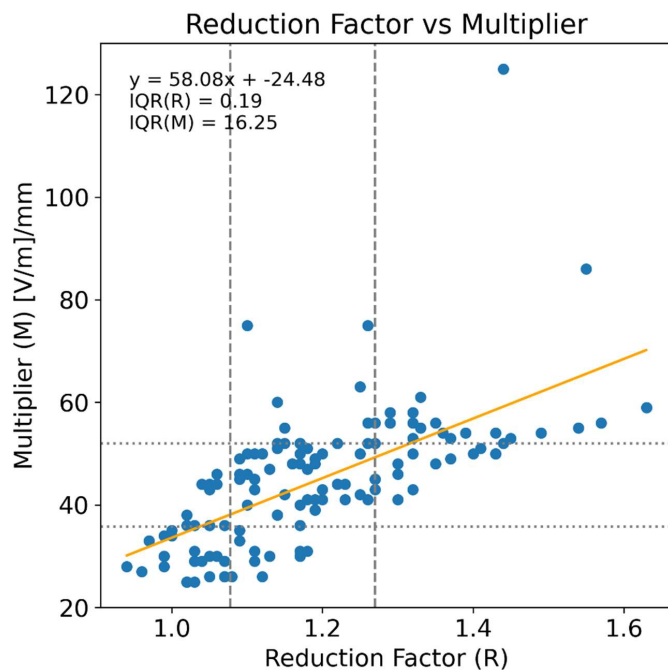
359 **Figure 5. Schematic illustration of the procedure used to convert original chart recorder deflexion measurements into**
 360 **tabulated potential gradient (PG) values.**

361 To illustrate how the measured value of chart deflexion D and multiplier M , were used to reconstruct PG measurements,
 362 Figure 5 presents the flow of the conversion process from chart recorder deflexion measurements to tabulated PG values.
 363 The conversion relies on M , derived from both the reduction factor (R) and chart recorder scale (S) calibration. The
 364 reduction factor was obtained through comparisons of the potential measured at a known height, as determined with a
 365 stretched-wire apparatus in an open part of the observatory site (HR22, fig 5). Variations in the multiplier and reduction
 366 factor for period 2 are presented in Figure 6.
 367 Figure 6a and 6c show the temporal variation of multiplier values and the reduction factor, respectively, between 1946 and
 368 1956. Most multiplier values are consistent and stable, although several pronounced peaks are visible, while higher
 369 reduction factors were generally observed from 1949 to 1951. The multiplier and reduction factor distribution are depicted
 370 in Figure 6b and 6d. Most multiplier values lie between 35 [V/m]/mm and 60 [V/m]/mm with IQR 16.25 [V/m]/mm,
 371 although several larger values are present, which seem likely to be associated with occasional changes in instrument or
 372 chart recorder settings. The reduction factor lies between approximately 1.0 and 1.4, most commonly around 1.07–1.27
 373 with IQR 0.19.
 374 Figure 7 shows the relationship between the reduction factor and multiplier values used for converting deflexion
 375 measurements into potential gradient (PG) values during Period 2. The vertical and horizontal dashed grey lines in Figure
 376 7 indicate the IQR boundaries of the reduction factor and multiplier distributions, respectively. The scatter plot shows a
 377 roughly linear relationship between the reduction factor and multiplier values, although several outliers are also visible.
 378 This suggests that the combined variability in the multiplier is influenced not only by the reduction factor, but also by
 379 variations in the chart recorder scale.



380

381 **Figure 6. Distribution and temporal variation of multiplier (a, b) and the reduction factor (b, d)**



382

383 **Figure 7. Scatter plot of reduction factor against multiplier used in Period 2 (1946–1956). The grey dashed lines show the**
 384 **boundaries of the IQR of the reduction factor and multiplier distributions, respectively.**

385



5.2 Characteristics of the dataset

Statistical characteristics of the digitized dataset are presented in Table 3. The table includes statistical parameters of the PG such as mean, median, standard deviation (STD), and IQR. It also summarises the minimum and maximum recorded PG values and provides information on data completeness for both periods 1 and 2 separately. The first six columns have been calculated for the entire digitized period (i.e. periods 1 and 2 together). Differences in the percentage of available data reflect the different recording practices between Period 1 and Period 2, particularly the reduced observation frequency in the later period. The Period 2 column also shows for hours 3, 9, 15, and 21, around 87-90% of the values exist, while for hours 1 and 24 the percentage is approximately 60%. For the remaining hours, the percentage is approximately 42%. Appendix Figure 3B shows the hourly time series across the entire period of the data.

Table 3. Hourly statistics of PG at Lerwick Observatory for 1927–1956, including measures of central tendency and variability, percentages of missing data for Periods 1 and 2, and the number of available observation days.

Hours	Characteristics of PG (V/m) measurements						Missing data (%)		N of available days
	From 1927 -1956						Period 1	Period 2	
	Mean	Median	Min	Max	STD	IQR			
1	150	125	-939	1151	129.01	88	45	59	5472
2	143	119	-715	1129	108.34	81	45	43	4841
3	136	113	-1573	2140	140.46	83	45	88	6619
4	134	111	-495	941	100.43	78	45	43	4819
5	136	112	-600	1112	102.66	79	45	43	4822
6	141	115	-451	1030	107.51	83	45	42	4795
7	147	122	-563	988	111.5	88	45	42	4785
8	154	128	-804	1248	112.47	91	45	42	4783
9	153	131	-1784	2679	151.84	94	45	87	6605
10	153	130	-573	1024	107.92	83	45	42	4785
11	149	128	-520	899	102.27	81	45	42	4779
12	148	129	-711	780	98.74	80	45	42	4781
13	150	130	-787	891	99.4	80	45	42	4780
14	155	135	-639	924	103.85	83	45	42	4780
15	157	141	-2102	2008	160.52	96	45	88	6651
16	166	143	-788	1075	111.31	88	45	42	4781
17	171	147	-607	854	110.03	89	45	42	4781
18	174	151	-475	867	109.5	91	45	42	4781
19	180	154	-465	954	115.44	91	45	42	4779
20	187	159	-380	910	119.64	96	45	42	4778
21	186	160	-2802	2481	165.39	107	45	90	6701
22	185	157	-1200	1241	126.72	98	45	42	4774
23	177	150	-559	1097	124.16	99	45	42	4774
24	164	137	-997	1016	129.42	96	45	58	5447

Figure 8 shows the monthly count of measurements in the digitized dataset over the period 1927–1956. The number of measurements varies considerably between months, reflecting differences in data availability and completeness in the



original records. Some months contain close to the expected number of measurements, i.e. from 672 measurements for a non-leap year February to 744 measurements for months of 31 days. Other months show substantially smaller counts, indicating missing days or incomplete hourly records. The figure also shows that the number of monthly measurements generally decreases during the winter months. This is likely related not only to reduced fair-weather conditions during that period, but also to operational difficulties. In Period 1, the median number of observations was 600 in winter (DJF) and 1320 in summer (JJA); whilst during Period 2 it increased from 820 in winter to 1561 in summer, indicating more complete summer records and improved overall coverage during the later period. More discussion can be found in Appendix (see Figure 4B in the Appendix).

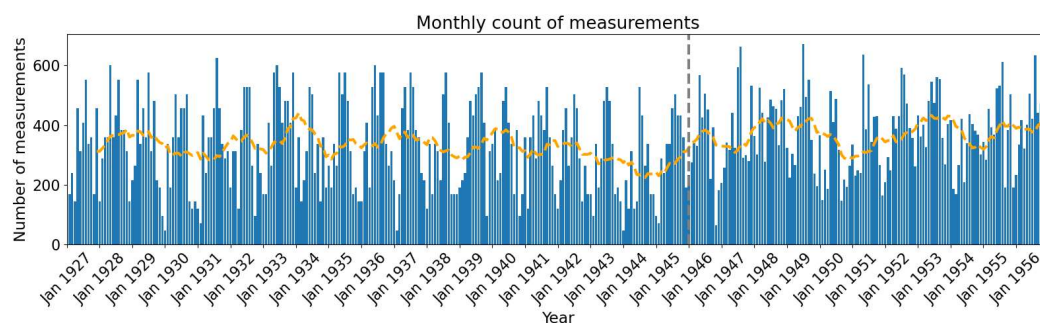


Figure 8. Monthly number of digitized measurements from Lerwick Observatory for the period 1927–1956. The vertical dashed grey line indicates the end of Period 1 and the start of Period 2, the orange dashed line shows the monthly mean of the number of measurements.

Overall, the figure highlights both the temporal coverage of the dataset and the presence of gaps in the observations that should be considered in further analyses.

5.3 Time series characteristics

Figure 9(a) shows the time series of PG measurements at 15:00 UT from Lerwick Observatory for the period 1927–1956 for all day types (i.e. 0, 1 and 2). This demonstrates a distinct change in the range of PG values between Period 1 and Period 2 (starting in 1946). For Period 1 the PG values were mostly positive, with extreme values within ± 1000 V/m. From 1946 onwards (Period 2), the PG variability is generally much larger, with extreme values double that of Period 1: -2800 V/m to 2679 V/m, with many more negative PG values. The change in PG variability between the two periods is investigated further in Figure 9(b), (c) and (d), which show measurements with day type 0, 1 and 2 respectively.

Figure 9(b) demonstrates the small variability in PG values for 0a days, with solely positive PG values and no obvious changes across the 30-year period. A change in variability between Period 1 and 2 is, however, evident in the day type 1 data (Figure 9(c)), and no day type 2 data was recorded before 1946 (Figure 9(d)). The increase in variability in the 15:00 UT PG for all day types (Figure 9(a)) is therefore likely to be due to the contributions of the day type 1 and day type 2 data (which is likely to contain disturbed weather data), rather than the day type 0 (which is consistent across the period). Since Figure 9 only shows the time series for 15:00 UT, a further figure (Figure 3B) in the Appendix investigates whether the variability change is present for other hours of the day. This indicates that 03:00 UT, 09:00 UT, 15:00 UT, and 21:00 UT PG values for Period 2 have substantially increased variability. These are the hours in which data were most frequently recorded (i.e. Period 2 data was often only recorded at 6 hourly intervals across the day), as Table 3 demonstrates.

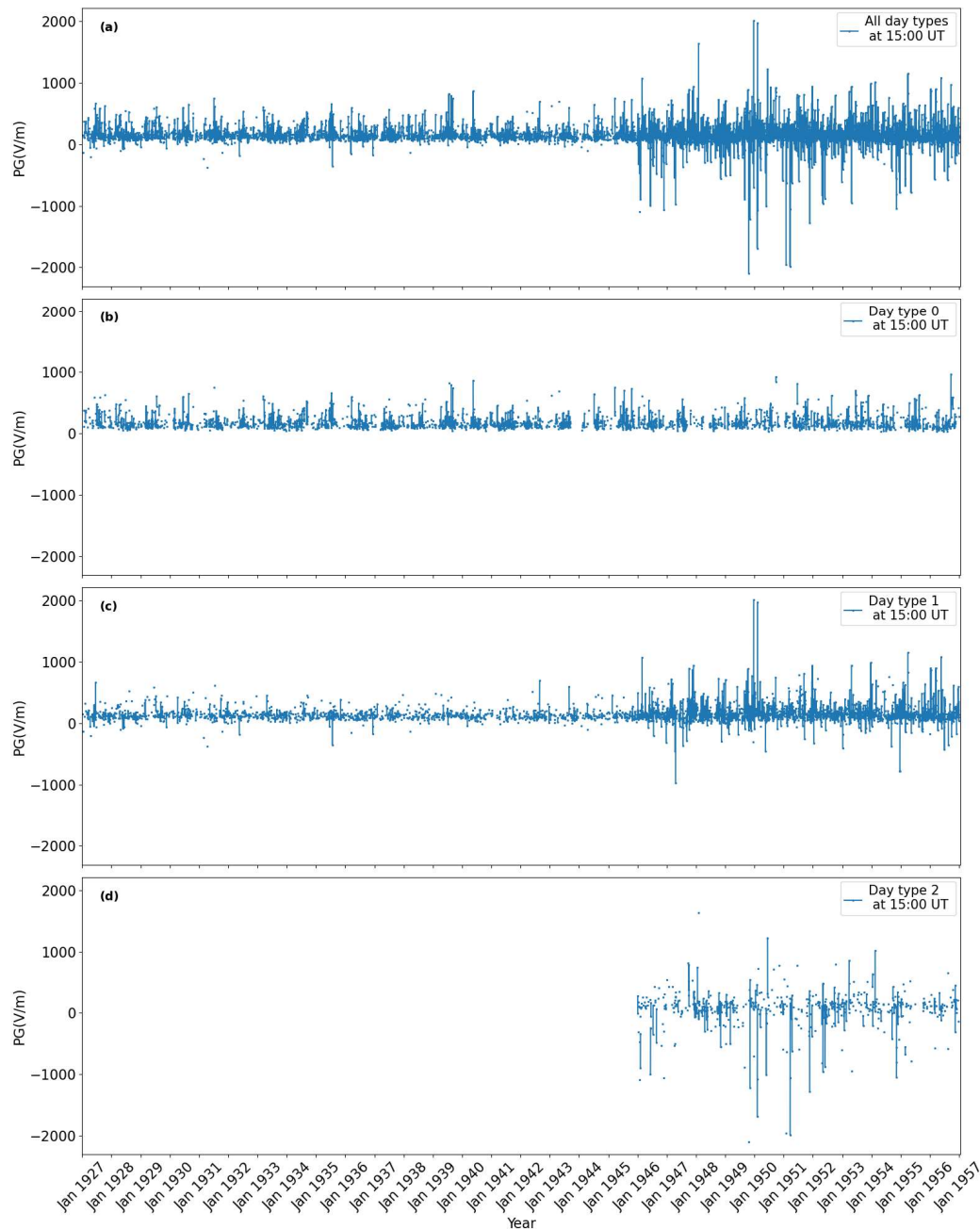


Figure 9. Time series of hourly PG measurements at 15:00 UT from Lerwick Observatory for the period 1927–1956. a) all day types, b) day type 0, c) day type 1, d) day type 2. (The range of the PG axis is restricted to ± 2000 V/m.)

5.4 Diurnal variation characteristics

Figure 10 investigates the diurnal variation in the Lerwick PG data averaged over the 30-year period in the dataset. The daily mean variation shows lower PG values during the early morning hours and higher values during the evening, with a



maximum around 20–22 UT, broadly consistent with the Carnegie curve (Figure 10(a)). Figure 10(b) presents the daily mean PG variation for different day types over the period 1927–1956, together with the Carnegie curve. Day type 0 shows the highest PG values throughout the day, while lower average values are observed for day types 1 and 2. This difference is likely to be related to negative PG excursions during disturbed weather conditions, which reduces the overall mean values for these day types.

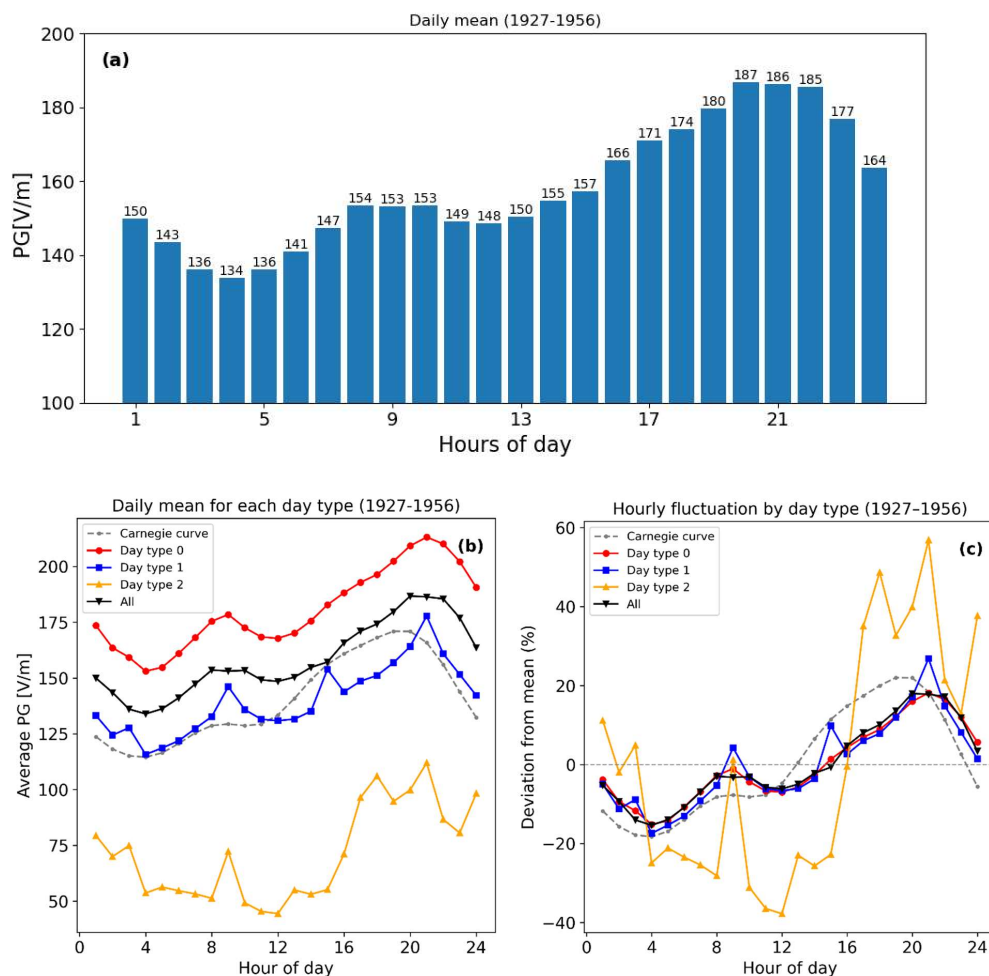


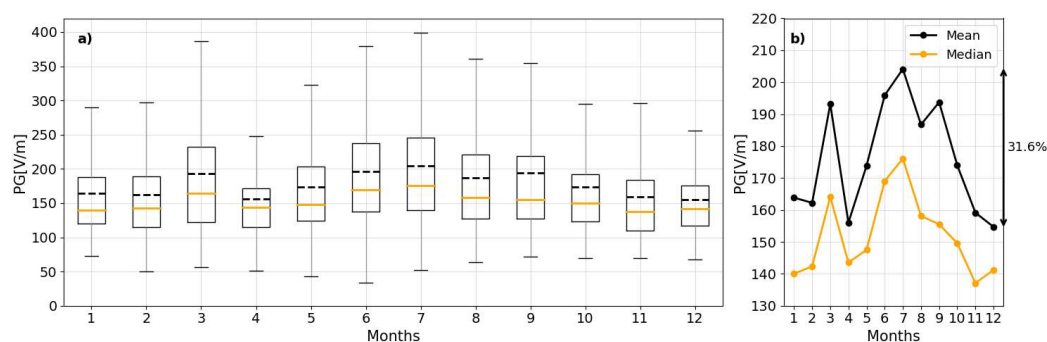
Figure 10. (a) Daily mean values of potential gradient (PG) at Lerwick Observatory during 1927–1956. Numbers above each bar represent the mean values. (b) Daily mean values for all day types as well as each individual day type, compared with the Carnegie curve (dotted-dashed line) and (c) associated relative hourly fluctuations of potential gradient (PG) at Lerwick Observatory for each day type.

5.5 Seasonal variation characteristics

Monthly and yearly average variations in PG are depicted in Figure 11 for the entire 30-year period for Day type 0. The boxplots in Figure 11(a) show the monthly PG distribution, which indicates a seasonal variation, with the highest PG values occurring during summer and early autumn months, while lower values are observed during winter. Figure 11 (b) displays the same data as in (a), only plotted without the variability, demonstrating the magnitude of the PG differences



454 between months more clearly. The shape of the trace, with a northern hemisphere summer maximum, and winter minimum,
 455 is broadly consistent with other studies investigating seasonal variability in surface PG, and also supports current theories
 456 on the likely seasonality in the GEC (e.g. Slyunyaev et al., 2025a). The magnitude of the percentage difference between
 457 seasonal minimum and maximum is found to be 32% at Lerwick, which is similar to that reported by Slyunyaev et al.,
 458 2025b for Vostok (between 16 - 30% depending on which corrections are applied to the raw data), which is generally
 459 thought to be representative of the GEC.
 460
 461



462
 463 **Figure 11. Monthly average (a,b) distribution of PG values at Lerwick Observatory for the period 1927–1956 (includes all**
 464 **hours of the day for Day type 0). The orange line indicates the median, and the black line the mean value.**

465 Recent literature discusses the dependence of the PG seasonality on the time of day of measurement (Slyunyaev et al.,
 466 2025a). Figure 12 therefore examines whether the time of day influences the PG seasonality by showing the monthly mean
 467 PG variation for each observation hour for day type 0. This is the first analysis of this kind for this dataset. A clear seasonal
 468 cycle is visible for many of the different hours of the day, with the same behaviour as the average variation shown in Figure
 469 11, with higher PG values during summer and lower values during winter months. The amplitude and shape of the seasonal
 470 variation do, however differ between the observation hour chosen. This likely reflects both the natural variability of
 471 atmospheric electricity and differences in data availability throughout the year.

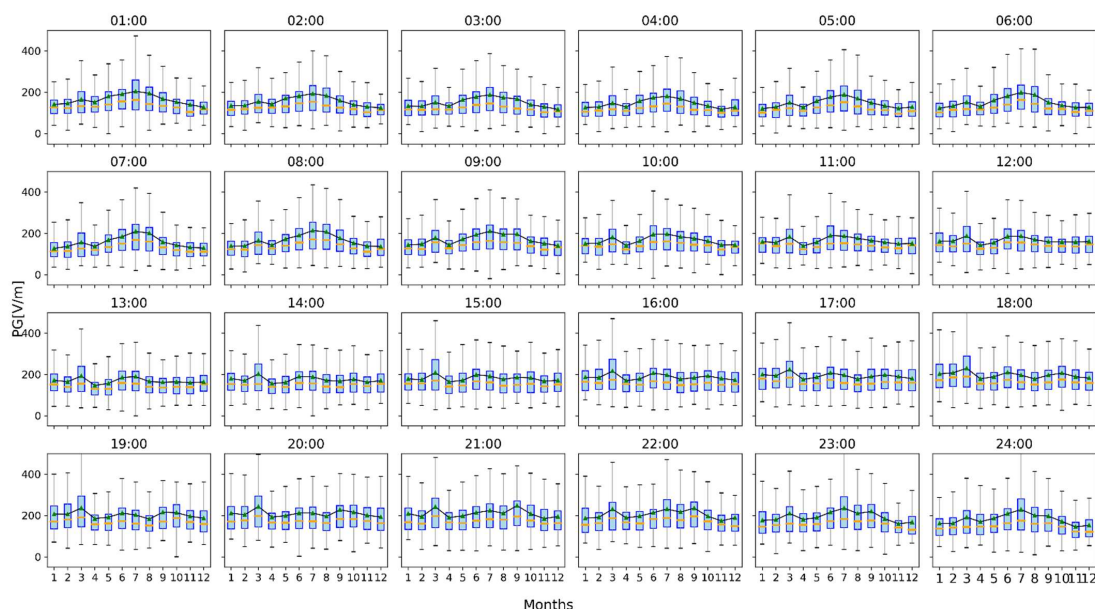


Figure 12. Monthly mean PG values for each observation hour during the period 1927–1956 for day type 0. Each panel represents the seasonal PG variation for a specific observation hour.

For the night and early morning hours, there is a clear summer maximum (roughly from 23:00–10:00) around June–August. However, for afternoon and evening hours (~14:00–20:00) the seasonal cycle weakens. The median PG values remain relatively similar throughout the year, and the monthly distributions are similar. For this period a summer maximum is not clearly present suggesting that seasonal effects are less pronounced than the diurnal variability. The dominance of the seasonal cycle for the early morning hours is consistent with observations reported at other locations, and particularly those shown in Figure 3 of Slyunyaev et al., 2025a, for Vostok, Antarctica, which demonstrates no clear seasonality for 15:00 UT. There is also a secondary peak in March shown in Figure 12 for Lerwick for most hours of the day (which is strongest during the afternoon and early evening hours), which is also consistent with the Vostok peaks around the spring and autumn equinoxes for 15:00 UT. This may be indicative of seasonal changes in convection, which modify regional contributions to the ionospheric potential as modelled by Slyunyaev et al., 2025b. This work reported that the contribution of the ionospheric potential to the GEC from near the equator (i.e. 9°S to 9°N latitude range) has two maxima, around the equinoxes; unlike the contribution of higher latitudes, which has one maximum during the local summer. Although the seasonality in the Lerwick PG supports the previous literature around seasonality in the GEC, further analysis is required to confirm whether this is a GEC effect or local one. For instance, there is a known influence on wind direction on the PG at Lerwick (Hamilton, 1965; Harrison and Nicoll, 2008), in which polluted air transported from Europe can increase PG under certain wind directions, namely from 100–210°. It is unknown how this affects the seasonality of PG at Lerwick, as regular wind direction measurements were not available during the periods considered here. It should also be noted that the number of values used in the calculation of the monthly mean/medians varies by month, with more values in the summer months than in winter. For the mean monthly PG values shown in Figure 11, the number of monthly values forming the mean varies from a maximum of 600 in June to a maximum of 353 in December. It is therefore possible that variation in the number of values during summer contributes to variability in the yearly summer PG maxima.



5.6 Annual variation characteristics

The yearly means (shown in Figure 13) are presented in the same format as for Figure 11. These show variability throughout the observation period, with some years demonstrating particularly high variability such as 1927, 1934 and 1950, although no strong long-term trend is immediately apparent. As in the monthly analysis, the mean consistently exceeds the median.

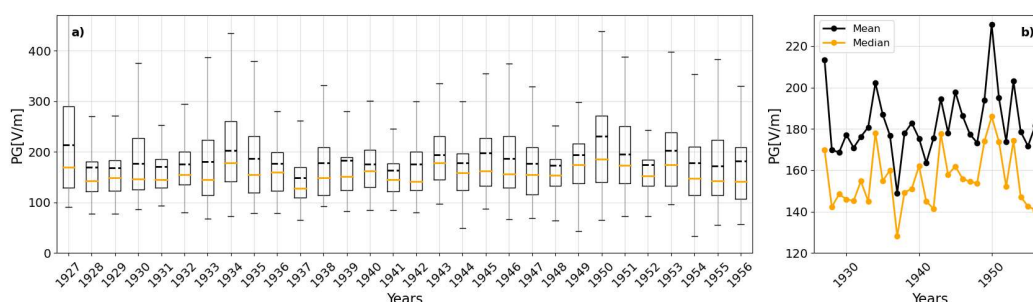


Figure 13. Yearly average (a,b) distribution of PG values at Lerwick Observatory for the period 1927–1956 (includes all hours of the day for Day type 0). The orange line indicates the median, and the black line the mean value.

6. Validation and data quality assessment

6.1 Comparison with independent reference data

The mean diurnal variation in the Lerwick PG dataset shows a pattern broadly consistent with the Carnegie curve, with smaller values during the early morning hours (minimum around 04:00 UT) and greater values during the evening (maximum around 20–22 UT) (Figure 10).

Day types 0 and 1 display a diurnal pattern which is similar to that of the Carnegie curve (albeit with different magnitude), while day type 2 shows a less regular variation, although an evening increase is still visible; again the curve representing all measurements follows the general shape of the Carnegie curve. The relative hourly fluctuation of PG from the daily mean (Figure 10(c)) shows a broadly similar diurnal pattern to the Carnegie curve for day types 0 and 1, with negative deviations during the early morning and positive deviations during the evening; the magnitude of the percentage change between minimum and maximum (± 15 to 20 %) is also similar to that of the Carnegie curve for day types 0 and 1. Day type 2 shows much larger fluctuations, likely related to the more frequent occurrence of negative PG measurements during disturbed weather conditions. Previous studies (HR22 Fig 8a and Harrison 2004, Fig 3a) have also shown good agreement between Lerwick observations and simultaneous Carnegie measurements, further supporting the validity of the digitized record. Similar seasonal variability has been reported in long-term fair-weather PG observations at Vostok Station (Slyunyaev et al., 2025a); the digitized Lerwick record adds further detail, allowing these seasonal variations to be examined separately for each observation hour.

6.2 Known limitations and data quality variations

There are clear differences between the printed form of the recorded sheets and the information tabulated between Period 1 (1927–1945) and Period 2 (1946–1956) which should be considered when using the dataset. In Period 1, each day's recorded generally contains observations for all 24 hours, whereas in Period 2 some days contain fewer than 24 hourly measurements; substantially more days of measurements are available for the observation hours 03, 09, 15 and 21 UT than



for other hours, and the number of observations generally decreases during winter, likely reflecting a combination of scientific (reduced fair weather) and, possibly, operational factors (staff availability). This uneven hourly and seasonal data coverage is a relevant consideration for future analyses using the dataset, for example in the constructing daily means, which may represent active source regions of the global circuit differently.

The Period 2 sheets also include deflexion and multiplier values which were not recorded separately in the Period 1. The multipliers used to convert deflexion measurements to PG values have been compared with the corresponding reduction factors for each day, and while a positive relationship is evident, considerable scatter indicates that additional factors, including stability of the chart recorder system, is likely to provide contribution to the observed variability.

The increased variability in the Period 2 data compared to Period 1 (Section 5.3) suggests a change in operating practice or equipment use, such as in the chart recorder used to record the measurements. The reason for this step change in variability in 1946 is not clear from the OYB as no change in recording practices or instrumentation is noted, but it may be that a wider range chart recorder was employed from 1946, allowing a greater range of values to be recorded; the increased variability in some hours and not others remains unexplained. In support of the wider range hypothesis, the 1938 OYB describes the range of the chart recorder as ± 1550 V/m, but the hourly PG values from 1946 onwards spanned -2800 V/m to $+2679$ V/m, clearly beyond this range. Since a range change would primarily affect observations in the “1” and “2” day type categories, this is a relevant consideration when assessing the long-term nature of the dataset for “all” day types and for these categories specifically. PG data on type 0a days was required to be <1000 V/m and positive, and unlikely to be affected by the range of the instrumentation or recording practices (Figure 9(b)); findings from 0a days can therefore be assumed to remain consistent over the 30-year period.

7. Discussion and Conclusions

The historical observations of atmospheric potential gradient at Lerwick are a unique dataset, relevant not only for atmospheric electricity studies, but more generally for studies of the Earth's atmosphere and climate variability, as well as solar-terrestrial studies. Previous investigations have demonstrated the value of Lerwick observations for examining long-term variability in the GEC, comparisons with the Carnegie curve, and links between atmospheric electricity and ENSO. In addition, because lightning is recognised as an Essential Climate Variable and it is linked with the GEC, long term PG observations offer a route to evaluating changes in global atmospheric electrification. The digitized Lerwick record may therefore contribute to future investigations of long-term variability in lightning-related climate processes and the response of the GEC to climate change. In addition, this dataset almost certainly represents the longest calibrated atmospheric electricity data series consistently using a radioactive equaliser probe sensor.

This work summarises the recovery of this historical dataset, through digitisation with a citizen science approach employing the Zoomiverse platform. Although recent advances in artificial intelligence (AI) and optical character recognition (OCR) methods continue to improve for the automated recognition of handwritten text, these approaches were not sufficiently reliable for the present dataset at the outset of the project. In part this is because the Lerwick sheets contain complex layouts, multiple variables, handwritten annotations, and formatting variations requiring human interpretation during digitization. In some cases, correctly associating measurements with the appropriate month, day type, or observation block depended on visual inspection by volunteers. Further, the number of available sheets was relatively limited for training a dedicated AI model, particularly given the heterogeneity of sheet structures and parameters recorded. For these reasons, a citizen science approach combined with manual verification provided a suitable approach for producing a



quality-controlled dataset. However, the later part of the dataset (1957–1983), which uses printed, tabulated values of a consistent form without the variability of handwritten records, is currently under digitization using AI-tools. Despite the variable nature of the source material, this work demonstrates that inconsistent and variably recorded data can be successfully digitized using a citizen science approach, transforming previously inaccessible scanned images into a dataset amenable to modern scientific processing.

Success of this digitization process can be evaluated in several ways. Firstly, the project enabled the recovery and digitization of a major part of the full historical dataset covering the period 1927–1956 at hourly resolution. Secondly, the citizen science approach attracted approximately 1800 volunteers, allowing each sheet to receive multiple independent classifications, which increased the reliability and accuracy of the digitized data. Data quality was assessed by manual verification of misplaced entries or through statistical aggregation methods to identify multiple entries from different contributors leading to non-zero IQR values, which together provide a reliable and quality-controlled dataset. For example, in Period 2 some volunteers occasionally confused the day and month values, which could only be resolved through manual verification. Section 4.2 and Section 6 detail the internal and external validation approaches used to build confidence in the dataset.

Overall, this work demonstrates that citizen science can be successfully applied to the large-scale digitization allowing long-term curation of complex historical scientific records. The resulting quality-controlled Lerwick PG dataset provides a valuable resource for future investigations of atmospheric electricity, the global electric circuit, and long-term climate variability.

Data availability

Data will be available in the University of Reading repository in .csv format. For initial review purposes, the data can be obtained from Zenodo <https://doi.org/10.5281/zenodo.23427164> , Mkrtchyan et al., 2026). The data files are temporarily placed under an embargo period while ongoing research is completed; during peer review, full access to the underlying data files is provided to the editor and reviewers via a confidential direct-access link.

The Carnegie data were obtained from Harrison, 2013.

Code availability

Custom Python scripts were used to process the digitized records, calculate quality-control statistics, aggregate volunteer transcriptions, and generate the analyses presented in this study. Because the final dataset also involved manual verification of entries flagged during quality control, complete reproduction of the published dataset requires both the scripts and the documented manual validation process. The scripts are available in GitHub:

<https://github.com/hripsime-mkrtchyan/AtmosEleC.git>

Author contributions

HM drafted the original manuscript, visualised the data, designed the Zooniverse project, processed the raw digitized data, and prepared the final verified database for uploading to the university repository. HM and KAN obtained the funding for the project. KAN provided advice and feedback on the design and testing of the Zooniverse project. RGH and KAN supervised and provided critical feedback and assisted in revising the manuscript. RGH identified and provided the original printed sheets for digitization and contributed expertise on the interpretation and understanding of the historical records.



604 AH revised the manuscript, contributed to the digitization process and carried out manual data verification and quality
 605 control of the dataset.

606 **Competing interests**

607 The contact author has declared that none of the authors has any competing interests

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622

623 **References**

- 624 Aich, V., Holzworth, R., et al.: Lightning: A New Essential Climate Variable. *Eos*, 99,
 625 <https://doi.org/10.1029/2018EO104583>, 2018.
- 626 Barnard, L., Portas AM, et al.: The National Eclipse Weather Experiment: An assessment of citizen scientist weather
 627 observations. *Philosoph Trans Royal Soc A Math Phys Eng Sci*, 374(2077):20150220,
 628 <https://doi.org/10.1098/rsta.2015.0220>, 2016.
- 629 Bonney, R., Cooper, C. B., et al.: Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific
 630 Literacy, *Bioscience*, 59, no. 11, 977–984, doi: 10.1525/bio.2009.59.11.9, 2009.
- 631 Bonney, R., Shirk, J. L., et al.: Next Steps for Citizen Science, *Science*, 343, no. 6178, 1436–1437,
 632 doi:10.1126/science.1251554, 2014.
- 633 Frissell N. A., Ackermann J. R. et al.: Heliophysics and amateur radio: citizen science collaborations for atmospheric,
 634 ionospheric, and space physics research and operations, *Front. Astron. Space Sci.*, 10:1184171, doi:
 635 10.3389/fspas.2023.1184171, 2023.
- 636 Grandin, M., Ledvina, V. E., et al.: Citizen Science in Space and Atmospheric Sciences: Opportunities and Challenges,
 637 *Surv Geophys*, <https://doi.org/10.1007/s10712-025-09888-6>, 2025.
- 638 Hamilton, R. A.: Secular and other changes of atmospheric electrical potential gradient at Lerwick, Q. J. R. Meteorol.
 639 Soc., 91, 348–352, 1965.



- 640 Harper, W. G.: Lerwick Observatory, *Meteorol. Mag.*, 79, 309–314, 1950.
- 641 Harrison, R. G.: Twentieth-century atmospheric electrical measurements at the observatories of Kew, Eskdalemuir and
642 Lerwick. *Weather*, 58(1), 11–19. <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1256/wea.239.01>, 2003.
- 643 Harrison, R. G. and Carslaw, K. S.: Ion–aerosol–cloud processes in the lower atmosphere, DOI:
644 10.1029/2002RG000114, 2003.
- 645 Harrison, R. G.: Long-term measurements of the global atmospheric electric circuit at Eskdalemuir, Scotland, 1911–
646 1981, *Atmos. Res.*, 70, 1–19, <https://doi.org/10.1016/j.atmosres.2003.09.007>, 2004
- 647 Harrison, R. G. and Nicoll, K. A.: Air-earth current density measurements at Lerwick; implications for seasonality in the
648 global electric circuit, *Atmospheric Research*, Volume 89, Issues 1–2, 2008, Pages 181–193, ISSN 0169-8095,
649 <https://doi.org/10.1016/j.atmosres.2008.01.008>, 2008.
- 650 Harrison, R. G., Joshi, M., and Pascoe, K.: Inferring convective responses to El Niño with atmospheric electricity
651 measurements at Shetland, *Environ. Res. Lett.*, 6, 044028, 2011.
- 652 Harrison, R. G.: The Carnegie Curve, *Surv. Geophys.*, 34, 209–232, <https://doi.org/10.1007/s10712-012-9210-2>, 2013.
- 653 Harrison, R. G. and Riddick, J. C.: Atmospheric electricity observations at Lerwick Geophysical Observatory, *Hist. Geo*
654 *Space. Sci.*, 13, 133–146, <https://doi.org/10.5194/hgss-13-133-2022>, 2022.
- 655 Harrison, R. G., Nicoll, K. A., et al.: Empirical evidence for multidecadal scale global atmospheric electric circuit
656 modulation by the El Niño–Southern Oscillation, *Environ. Res. Lett.*, 17, 124032, DOI 10.1088/1748-9326/aca68c, 2022
- 657 Harrison, R. G., Nicoll, K., and Mkrtchyan, H.: Lerwick Observatory monthly mean Potential Gradient 1925–1984,
658 University of Reading, Dataset, <https://doi.org/10.17864/1947.000505>, 2023.
- 659 Harrison, R. G., Mkrtchyan, H., and Nicoll, K. A.: Atmospheric Electricity Data From Lerwick During 1964 to 1984,
660 *Geoscience Data Journal*, 12, 3, <https://doi.org/10.1002/gdj3.70009>, 2025.
- 661 Kleimenova, N. G., Odzimek, A., et al.: Geomagnetic storms and substorms as space weather influence on atmospheric
662 electric field variations, *Sun and Geosphere*, 13(1), 101–107, 2018.
- 663 Krukowski, S., Amarasinghe, I., et al.: Does volunteer engagement pay off? An analysis of user participation in online
664 citizen science projects, In *Collaboration Technologies and Social Computing: 28th International Conference*,
665 *Proceedings. Springer-Verlag, Berlin, Heidelberg*, 67–82. https://doi.org/10.1007/978-3-031-20218-6_5, CollabTech,
666 2022.
- 667 Mkrtchyan, H., Harrison, G., and Nicoll, A.: Lerwick Observatory monthly mean Potential Gradient by hour of day 1964–
668 1984, University of Reading, Dataset, <https://doi.org/10.17864/1947.001367>, 2024.
- 669 Mkrtchyan, H., Harrison, R. G., and Nicoll, K.: Lerwick PG data from 1927–1956, Zenodo [data set],
670 <https://doi.org/10.5281/zenodo.23427164>, 2026.
- 671 Nicoll, K. A., Harrison, R. G., et al.: A global atmospheric electricity monitoring network for climate and geophysical
672 research, *Journal of Atmospheric and Solar-Terrestrial Physics*, Volume 184, Pages 18–29, ISSN 1364-6826,
673 <https://doi.org/10.1016/j.jastp.2019.01.003>, 2019.
- 674 Robles C., Amos H. et al.: Clouds around the World: How a Simple Citizen Science Data Challenge Became a
675 Worldwide Success, *Bull. Amer. Meteor. Soc.*, 101, E1201–E1213, <https://doi.org/10.1175/BAMS-D-19-0295.1>, 2020.
- 676 Rycroft, M. J. and Harrison, R. G.: Electromagnetic Atmosphere-Plasma Coupling: The Global Atmospheric Electric
677 Circuit, *Space Sci Rev*, 168, 363–384, <https://doi.org/10.1007/s11214-011-9830-8>, 2012.
- 678 Simpson, R., Page, K. R., and De Roure, D.: Zooniverse: observing the world's largest citizen science platform, In
679 *Proceedings of the 23rd International World Wide Web Conference (WWW 2014)*,
680 <https://doi.org/10.1145/2567948.2579215>, 2014.



- 681 Slyunyaev, N. N., Sarafanov, F., et al.: The seasonal variation of the direct current global electric circuit: 1. A new
 682 analysis based on long-term measurements in Antarctica, *J. Geophys. Res. Atmos.* (130),
 683 <https://doi.org/10.1029/2024JD042634>, 2025a.
- 684 Slyunyaev, N. N., Sarafanov, F. G., et al. The seasonal variation of the direct current global electric circuit: 2. Further
 685 analysis based on simulations. *J. Geophys. Res. Atmospheres*, 130(8), e2024JD042634, 2025b.
- 686 Whipple, F. J. W.: On the association of the diurnal variation of electric potential gradient in fine weather with the
 687 distribution of thunderstorms over the globe, *Q. J. Roy. Meteor. Soc.*, 55, 1–18, 1929.
- 688 Whipple, F. J. W., and Scrase, F. J. Point discharge in the electric field of the earth, an analysis of continuous records
 689 obtained at Kew observatory. *H. M. Stationery off*, 1936.
- 690 Williams E R: Lightning and climate: a review, *Atmos. Res.* 76, 272–87, DOI: 10.1016/j.atmosres.2004.11.014, 2005.
- 691 Williams, E.R.: The global electrical circuit: A review, *Atmos. Res.* 91 (2–4), 140–152,
 692 <https://doi.org/10.1016/j.atmosres.2008.05.018>, 2009.
- 693 Wilson, C. T. R.: Investigations on lightning discharges and on the electric field of thunderstorms. *Philos. Trans. Roy.*
 694 *Soc., A*, 221 (582–593), 73–115, doi: 10.1098/rsta.1921.0003, 1921.
- 695 Wilson, C. T. R.: Some thundercloud problems, *J. Franklin Inst.*, 208, 1–12, doi:10.1016/S0016-0032(29)90935-2, 1929.



Appendix A - Volunteer involvement

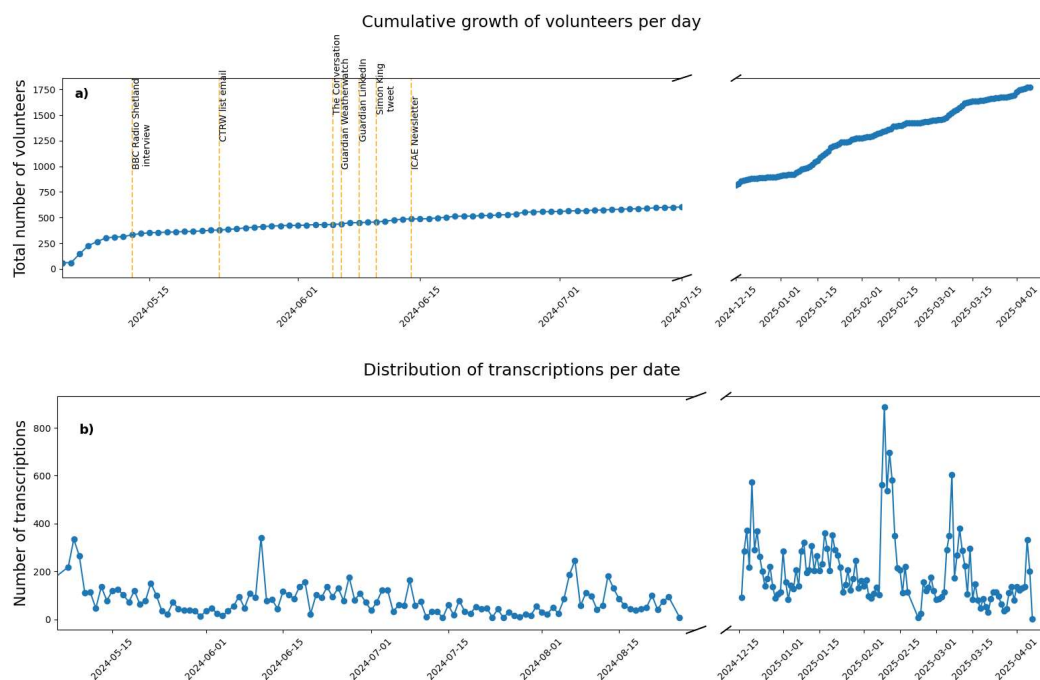
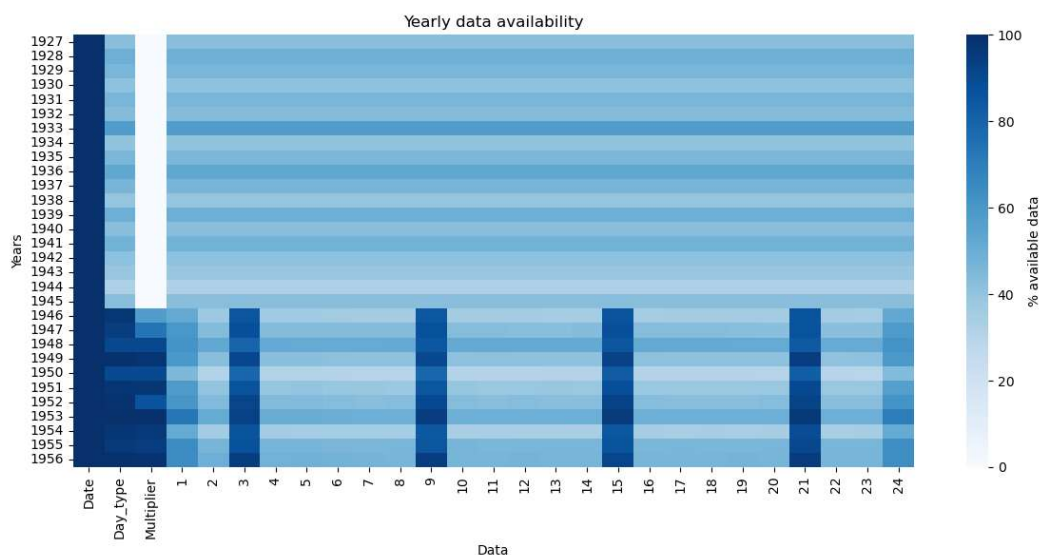


Figure A1. Volunteer participation and transcription activity during the Zooniverse digitization project. The panels show (a) the cumulative growth in the number of volunteers, (b) the daily distribution of completed transcriptions across both workflows.

Figure 1A illustrates the evolution of volunteer participation throughout the project. The cumulative growth plot shows a steady increase in the number of contributors, with noticeable increases following outreach and media engagement activities (shown by orange dashed lines). The second and third panels show the daily distribution of volunteers and transcriptions, respectively. The gap (August – December 2024) visible in the middle of the latter two plots corresponds to the transition period between the two workflows, during which volunteers were migrating to a different workflow.



709 Appendix B: Database information



710

711 **Figure B1. Heatmap of yearly data availability showing the percentage of recorded values for each variable and hour.**

712 The heatmap illustrates the yearly data availability of the digitized dataset, with years shown on the vertical axis and
 713 variables on the horizontal axis. The blue colour scale represents the percentage of available data, where darker shades
 714 indicate higher completeness. A clear difference is observed between Period 1 (1927–1945) and Period 2 (1946–1956). In
 715 Period 1, data availability is generally more uniform across hours, reflecting the more consistent recording structure. In
 716 contrast, Period 2 shows strong variability in hourly coverage, with certain hours (e.g., around 1, 3, 9, 15, 21 and 24)
 717 having higher data availability.

718 Figure 2B illustrates the statistical distribution of PG values at each observation hour for different periods of the dataset.

719 The histograms show that the distributions are generally asymmetric. Differences between the periods are also visible,
 720 particularly in the spread and variability of some hourly distributions, which may be related to data availability after 1945.

721

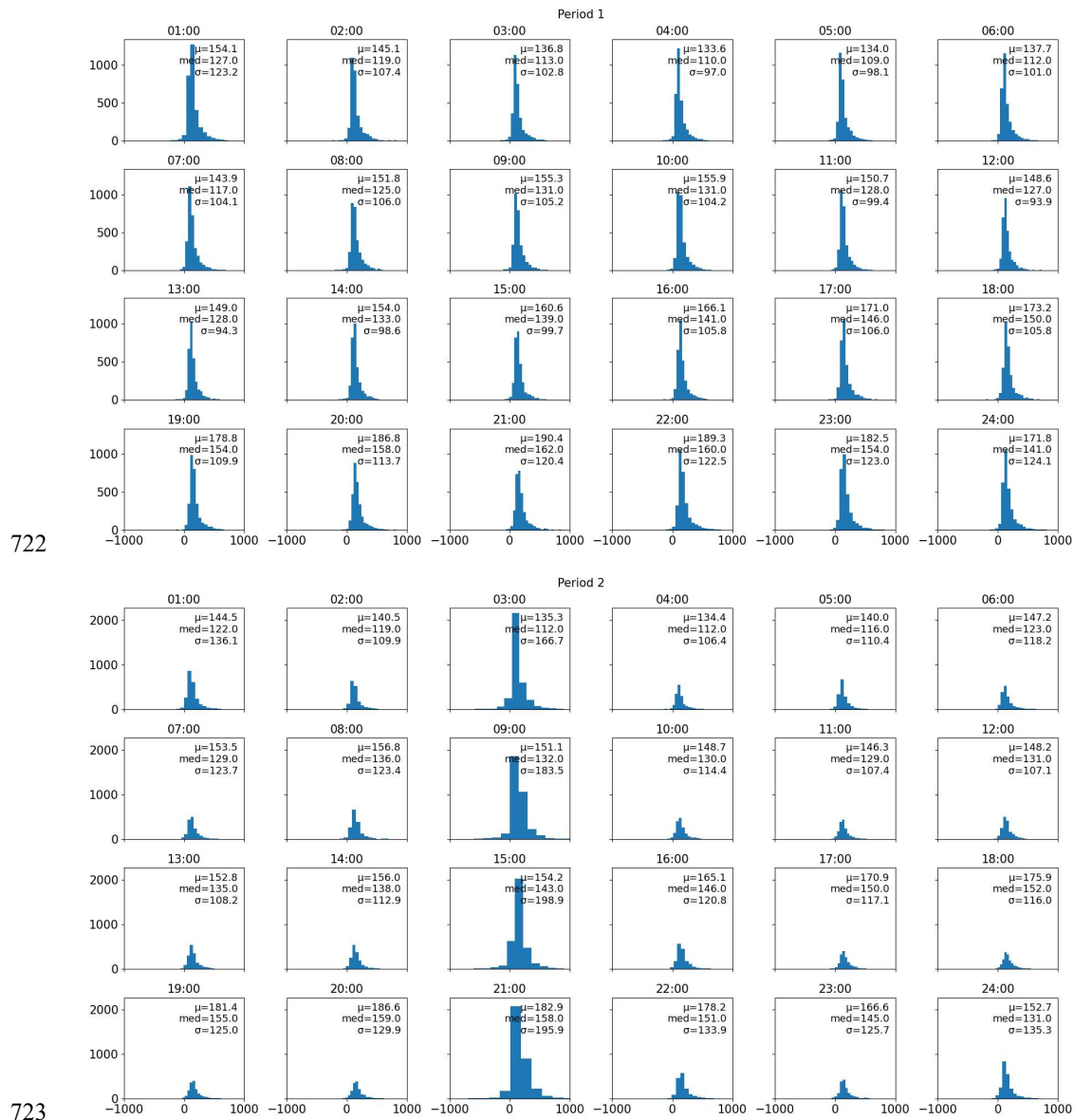


Figure B2. Hourly histograms of potential gradient (PG) measurements for each hour of the day. Separate sets of histograms are shown for measurements recorded during Periods 1 and 2. Each panel includes the mean (μ), median (med), and standard deviation (σ) of the corresponding hourly distribution.

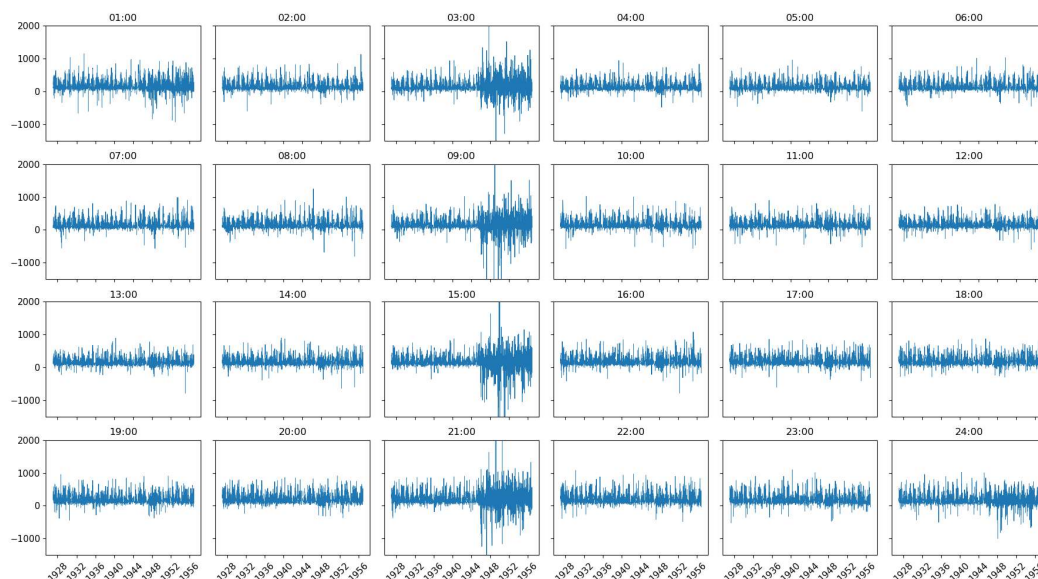


Figure B3. Hourly time series of PG measurements for the period from 1927 to 1956. Each panel represents the mean variation of PG for a specific observation hour.

Figure 3B presents the hourly PG time series for all observation hours across the full 1927–1956 dataset. The plots illustrate the characteristics of the PG measurements over time, including both positive and negative PG excursions. Increased variability is particularly noticeable for some hours after the mid-1940s, likely reflecting changes in recording practices, such as during disturbed weather conditions. The figure also highlights the presence of occasional extreme values.

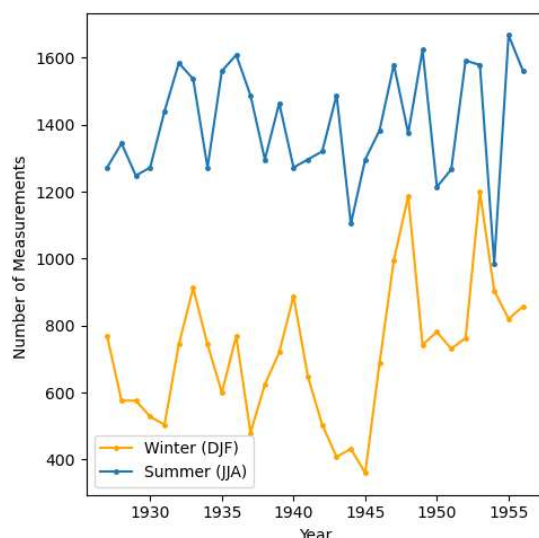


Figure B4. Annual number of available Lerwick PG measurements during Winter (December–February, DJF) and summer (June–August, JJA) for the period 1927–1956.

The figure illustrates the consistently greater number of summer observations compared with winter observations for all day types.