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HISTORICAL EVENTS AND OBSERVATIONS OPEN ACCESS

Historical geomagnetic observations from the Netherlands during the Carrington event (1859)

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Abstract – The Carrington event of September 1859 is the best known example of an extreme geomagnetic storm, often cited when discussing space weather risks for modern infrastructure. Historic observations including auroral sightings, magnetometer records and anecdotes of impacts on telegraph systems have been widely shared before, but none of these have included observations from the Netherlands. Geomagnetic observations taken in Utrecht and Den Helder during the Carrington event were digitised from the Royal Netherlands Meteorological Institute's (KNMI) yearbook of 1859, and compared to much more detailed magnetograms from London. This combined analysis, beyond its application in communication with Dutch stakeholders, contributes to a better understanding of the interpretation, limitations, and uses of such archived measurements, of which more examples might be available in archives internationally. The observations consist of spot measurements taken three times per day. The Den Helder data only partially record the Carrington storm. Conversion factors from Den Helder have been used to estimate missing conversion factors of the Utrecht data. The correlation between the Dutch declination measurements and those made in London is strong with correlation coefficients larger than 0.7 for the Utrecht data and larger than 0.9 for the Den Helder data. However, there is very little correlation between the Dutch and British inclination measurements. The London horizontal intensity measurements compared to Den Helder data give correlation values larger than 0.8 but the observations from Utrecht match less well. There is a significant deviation between the British data and the Utrecht declination and horizontal intensity measurements during the quiet period between 30 August and 2 September. It is unclear what causes this deviation. Given the proximity of the locations and similarity in latitude, and based on the coherent registration of the measurements, it is reasonable to assume that the magnetic traces captured in London provide a good approximation of the magnetic field variations in the Netherlands during the storm, indicating that these may be used for impact assessment studies for Dutch vital infrastructure.

Keywords: Space weather / Space climate / Carrington event / Historical observations

1 Introduction

Extreme geomagnetic storms can potentially have large impacts on society (Astafyeva et al., 2014; Kappenman, 2005). Moreover, because of the growing reliance on advanced technologies such as satellite services, modern society is at risk of becoming increasingly vulnerable to severe space weather (Hapgood et al., 2021). Understanding and modelling the potential adverse effects of severe space weather requires extensive multi-instrument, synoptic registrations of large events. However, as such extreme occurrences are very rare in the modern era of space based instrumentation, we must also look to historical geomagnetic measurements made during large events to assess the magnitude and progression of the largest geomagnetic storms.

A well known example is the Carrington event, which occurred during a period of very severe space weather in late August and early September 1859 (Green & Boardsen, 2006; Hayakawa et al., 2022; Cliver & Dietrich, 2013). Following a geomagnetic storm several days earlier, Richard Carrington serendipitously viewed one of the strongest solar flares in observational history (estimated to be ~X64 by Cliver et al. (2022) and ~X80 by Hayakawa et al. (2023)). The flare was a rare event with a return period of about 60–90 years (Curto et al., 2016). The flare was followed by a second strong geomagnetic storm causing auroral sightings all over the world. Reconstruc-

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tion of the spatial evolution of the auroral oval from historical records indicates that it concerned a very strong, but not unique, storm (Hayakawa et al., 2019). Still, an extreme magnetic excursion of ~ -1600 nT was measured in Bombay (Tsurutani et al., 2003) whose cause and interpretation is still subject of discussion (Siscoe et al., 2006; Akasofu & Kamide, 2005; Cliver & Dietrich, 2013; Cid et al., 2014; Hayakawa et al., 2022, and references therein). The individual aspects of the solar storm have close rivals or superiors in recorded history (Cliver & Svalgaard, 2004; Cliver et al., 2022). According to Love (2021), a once-per-century storm has a Dst index of -663 nT.

Recently, magnetogram records of the Carrington geomagnetic storms observed in Kew and Greenwich (London, UK) have been digitised and made publicly available (Beggan et al., 2023, 2024). The declination as well as the horizontal and vertical components are provided for the 10-day period from 25 August to 5 September 1859 with a nominal time resolution of one minute. Other investigations for historical magnetic measurements during the Carrington event have been made in Finland and Russia (Nevanlinna, 2008), Rome (Blake et al., 2020) and India (Hayakawa et al., 2022), all have significantly lower time resolutions than the London measurements but higher than the measurements from the Netherlands presented below.

KNMI has a long history in the field of geomagnetic measurements. Regular measurements started in 1849, several years before KNMI's formal establishment in 1854, and lasted until 1988 when the geomagnetic research activities ceased because of budget cuts. In this almost 140 year period geomagnetic field variations were observed in Utrecht (1849–1899), De Bilt (1899–1938) and Witteveen (1938–1988). KNMI's earliest yearbooks (1854–1883) also contain geomagnetic observations made in Den Helder by Provinciale Waterstaat, the organisation that was responsible for practical execution of the public works and water management in the province of Noord-Holland. These Den Helder records continue until (including) 1883. It is unknown whether geomagnetic measurements were made in Den Helder after 1883. The yearbook of 1887 (Koninklijk Nederlandsch Meteorologisch Instituut, 1888, page 275) states that Utrecht is the only measuring site in the Netherlands, indicating that the Den Helder activities had stopped by then.

The yearbooks of 1884 and 1885 only contain absolute measurements of the field made several times per year in Utrecht. As of 1886 monthly averages are included of measurements daily made at 14:00 local time. Starting from 1892 magnetic traces are available in KNMI's archives. The first year this only concerned declination observations, of which the measurement method is described in the yearbook of 1893 (Koninklijk Nederlandsch Meteorologisch Instituut, 1895, page 353). The same yearbook also lists the hourly declination measurements. From 1894 onwards hourly horizontal intensity measurements are recorded in the yearbooks, of which the instrument is described in the yearbook of 1894 (Koninklijk Nederlandsch Meteorologisch Instituut, 1896, page 343). Several years later in 1902 hourly values of the vertical intensity are added to the yearbook. As of 1903 a new department for magnetic measurements and seismology was founded at KNMI. From then onwards the geomagnetic measurements were published in separate dedicated yearbooks. Digitised hourly data from the Netherlands, from 1903 until the end of operations of the Witteveen magnetic observatory in 1988, are available via the World Data Centre for Geomagnetism, Edinburgh (Reay et al., 2013).

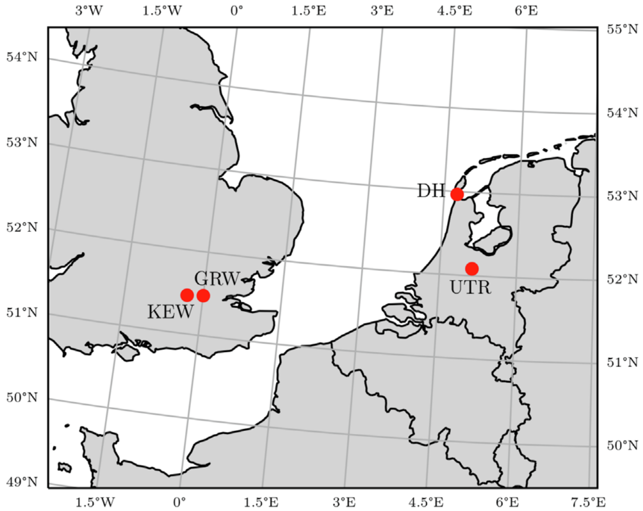


Figure 1. Map of Northwestern Europe with present-day borders displaying the locations of the magnetic observation sites of Kew, Greenwich (GRW), Den Helder (DH) and Utrecht (UTR) in 1859.

Table 1. Geographical coordinates of the magnetic observation sites.

	Longitude [°E]	Latitude [°N]
Den Helder (DH)	4.75	52.964
Utrecht (UTR)	5.13	52.085
Greenwich (GRW)	0.00	51.483
Kew (KEW)	−0.31	51.463

In this article geomagnetic observations made in Utrecht and Den Helder during the Carrington event are digitised from KNMI's yearbook of 1859 (Koninklijk Nederlandsch Meteorologisch Instituut, 1860), and compared to magnetograms taken in Kew and Greenwich. All four observation sites have comparable latitudes (Fig. 1). Their coordinates are listed in Table 1. Examples of historical observations from the Netherlands and surrounding countries during extreme events are useful in communication with Dutch space weather stakeholders. Comparing these datasets allows for cross-verification of the scaling techniques used in the digitisation, and to assess whether the more complete historical data from the United Kingdom could be used for studies on the impact of geomagnetic storms in the Netherlands.

2 Instrumentation

The yearbooks of 1853 (Koninklijk Nederlandsch Meteorologisch Instituut, 1854, page V), 1855 (Koninklijk Nederlandsch Meteorologisch Instituut, 1856, page VI), 1856 (Koninklijk Nederlandsch Meteorologisch Instituut, 1857, page VI) and 1857 (Koninklijk Nederlandsch Meteorologisch Instituut, 1858, page II) as well as a book by Krecke (1849) provide descriptions of the instrumentation that was used at the observatories. All instruments are variometers. Excerpts mentioning the measurement equipment have been collected in the Supplementary material (in Dutch and French with English translations). The declination instrument used in Utrecht is best described. It was built by E. Wenckeback in Amsterdam following the description given by von Lamont (1849) in Munich. A magnetic needle of 70 mm by 7 mm with a small mirror perpendicularly fixed above its center was suspended from a 18 cm silk thread passing through a glass tube and would point in the direction of the magnetic meridian. The needle resided in a slot within a 118 mm copper disc, enclosed by glass and copper plates to protect it from air agitation. The instrument rested on three screws and was positioned on a pillar fixed in the vaults of the observatory, a former bastion fort called 'Sonnenborgh'. On a second pillar a telescope and an ivory millimeter scale were placed which were both attached to a solid copper plate. The distance between the pillars is said to be such that one millimeter of the scale corresponds to approximately one arcminute. It is ambiguous whether this means that when looking from the central point of the mirror to the scale one millimeter corresponds to one arcmin (~3.4 m), or that when looking through the telescope a deflection of the mirror by one arcmin corresponds to 1 millimeter on the scale (~1.7 m). In the latter case both angle of incidence and angle of reflection need to be taken into account. When looking at the scale through the telescope via the mirror, the divisions on the scale could be easily estimated in tenths of millimeters (i.e. tenths of arcminutes). Small changes in the magnetic meridian, and thus in the declination, were measured this way.

The other variometers in both Utrecht and Den Helder are described in much less detail. The Utrecht instrument to measure variation in the horizontal intensity (H-variometer) is only said to consist of a magnetic needle suspended by a fine glass fibre, with the upper part of the fibre attached to a torsion circle. It was built following the descriptions by Lamont and, as only a singular fibre is mentioned, it is assumed that a unifilar device was used, contrary to the bifilar (two threads) instrument also described in Lamont's book which was often used in other contemporary observatories. For a modern description of the bifilar instrument see Hejda et al. (2023) and Nevanlinna (1997). In the unifilar instrument a magnetic needle is suspended from an often metal wire (glass fibre in Utrecht) and hung in the average direction of the diurnally changing magnetic meridian. The upper end of the wire is then rotated by the angle ψ so that the needle is deflected by an angle ϕ from the meridian. This gives the equation (von Lamont, 1849, page 200):

$$\gamma(\psi-\phi)=MX(1-\alpha t)\sin\phi \tag{1}$$

with γ the torsion constant, M the magnetic moment of the needle, X the horizontal intensity, α a temperature coefficient, and t the temperature. Note that factor $(1-\alpha t)$ is needed to take into account the dependence of γ and M on temperature changes with respect to a reference temperature ($\Delta t = t - t_0$). If the magnetic meridian shifts by the small angle ε in the direction of ϕ (change of declination), the force pulling the needle away from direction ψ becomes smaller, and the equation becomes:

$$\gamma(\psi-\phi)=MX(1-\alpha t)\sin(\phi-\varepsilon) \tag{2}$$

From this equation X can be isolated, which is a function of the deflection angle ϕ and the temperature t:

$$X(\phi,t)=\frac{\gamma(\psi-\phi)}{M(1-\alpha t)\sin(\phi-\varepsilon)} \tag{3}$$

Taking the partial derivatives of the logarithm of X at the reference values (ϕ_0, t_0),

$$d\ln(X)=\left(\frac{\partial\ln(X)}{\partial\phi}d\phi+\frac{\partial\ln(X)}{\partial t}dt\right)\Bigg|_{(\phi_0,t_0)} \tag{4}$$

and replacing differentials by differences ($dX\to\Delta X$, $d\phi\to\Delta\phi$, $dt\to\Delta t$) gives

$$\frac{\Delta X}{X}=\frac{\Delta\phi}{\psi-\phi_0}-\frac{\Delta\phi}{\tan(\phi_0-\varepsilon)}+\frac{\alpha\Delta t}{1-\alpha t_0} \tag{5}$$

Lamont suggests to choose ϕ_0 such that it makes an almost 90° with the average meridian, i.e. $\phi_0 = 90° + x$ with x the small remaining deviation determined after setting up the instrument. By doing this the use of the *tan* function can be avoided (small angle approximation):

$$\frac{\Delta X}{X}=\frac{\Delta\phi}{\psi-90-x}+\Delta\phi(x-\varepsilon)+\frac{\alpha\Delta t}{1-\alpha t_0} \tag{6}$$

The change of the needle direction $\Delta\phi$ can be measured using a mirror, scale and telescope, similarly to the declination instrument described earlier. The effect of small changes in declination, i.e. small ε, on the horizontal intensity measurement is negligible. Lamont provides several example values with which states: "If the variations in intensity are to be determined with an accuracy of 1/100 of their magnitude, the movement of the declination may only be neglected if it is smaller than 24 arcminutes." The diurnal variation is well within this value. In the yearbooks it is said that for the Utrecht instruments no temperature corrections have been applied, suggesting that the last term in equation (6) was disregarded. The magnetic observation room was partly underground and the temperature changed only very slowly and very regularly. For H-variometer in Den Helder the yearbooks only state that "the magnets, which serve to deflect the needle, have also undergone a fairly regular decrease in strength over the course of the year." These auxiliary magnets are not further described but they were probably used to compensate for the temperature effects (von Lamont, 1849, page 206), indicating that in Den Helder a temperature correction was applied. The temperature at the Den Helder observatory is not discussed, nor whether a unifilar or bifilar device was used.

The inclination variometers are ill described in the yearbooks. Except for the "continuous increase of the magnetic force in the soft iron rods of the inclination instrument" in Den Helder there is no mention about their properties. According to von Lamont (1849, page 213) the method relies on two vertically placed soft iron rods which become magnetised via the induction of the geomagnetic field. The strength of the induced magnetism is proportional to the inducing force, i.e. the vertical component of the Earth's magnetism, and can therefore be represented by a $aJ\sin i$, with J the total force, i the inclination and a a constant. A suspended magnetic needle which can freely move in the horizontal plane is now deflected by angle ϕ from the magnetic meridian due to the influence of the magnetised bars. The equilibrium between the two forces is given by:

$$MX \sin\phi = aMJ \sin i \tag{7}$$

and by expressing horizontal intensity X as function of J, this becomes:

$$MJ \cos i \sin\phi = aMJ \sin i \tag{8}$$

Note that, contrary to equation (1), here no temperature effects are considered. The equation can be rewritten as:

$$\frac{\sin i}{\cos i} = \frac{\sin\phi}{a} \tag{9}$$

Now, Lamont applies the same logarithmic differentiation he also used for the H-variometer:

$$d \ln\left(\frac{\sin i}{\cos i}\right) = \frac{\partial}{\partial\phi} \ln\left(\frac{\sin\phi}{a}\right) d\phi\Big|_{\phi_0} \tag{10}$$

by applying the chain rule the left hand side becomes:

$$\begin{aligned} &\left(\frac{1}{\sin i}\right) \times (\cos i) \times di - \left(\frac{1}{\cos i}\right) \times (-\sin i) \times di \\ &= \left(\frac{\cos i}{\sin i}\right) di + \left(\frac{\sin i}{\cos i}\right) di = \frac{2}{\sin(2i)} di \end{aligned} \tag{11}$$

which, by replacing the differentials with differences ($di \rightarrow \Delta i$, $d\phi \rightarrow \Delta\phi$), gives:

$$\Delta i = \left(\frac{\sin(2i)}{2 \tan\phi_0}\right) \Delta\phi \tag{12}$$

From the observed change $\Delta\phi$ of the deflection angle, the change Δi of the inclination can thus be derived.

3 Dataset

Figure 2 shows a page of KNMI's yearbook of 1859 listing the observations made by F.W.C. Krecke, Directeur Waarnemingen ter Land (Director of Land Observations) in September 1859. The last three major columns left from the remarks section denote the declination, inclination and horizontal intensity measurements. The observations are spot measurements taken three times per day: in the morning at 08:00, early afternoon at 14:00 and evening at 22:00. All measurements were done in local astronomical time which is approximately 20 min earlier than Greenwich astronomical time. In astronomical convention 0 h means noon and 12 h midnight (Hejda et al., 2021). For each component there are three sub-columns of which the central sub-column lists the observed value at 14:00 in 'schaaldelen' (scale parts). The left sub-column lists the difference between the values observed at 14:00 and 08:00 ($D_{14:00}$–$D_{08:00}$) and the right sub-column lists the difference between the values observed at 14:00 and 22:00 ($D_{14:00}$–$D_{22:00}$). In Den Helder the observations were taken by Cornelis van der Sterr, superintendent of Provinciale Waterstaat of Noord-Holland. There the evening observations were made at 20:00 instead of 22:00.

The left plots in Figure 3 show the digitised data for the months of August and September 1859 converted to universal time (UT). From top to bottom the declination, inclination and horizontal force are shown in units of 'schaaldelen' (scale parts). The red and black lines denote the measurements in Utrecht and Den Helder respectively. The storm of 2 September clearly stands out in the Utrecht data whereas no values from Den Helder are available; in the yearbook it only states 'storing' (disturbance).

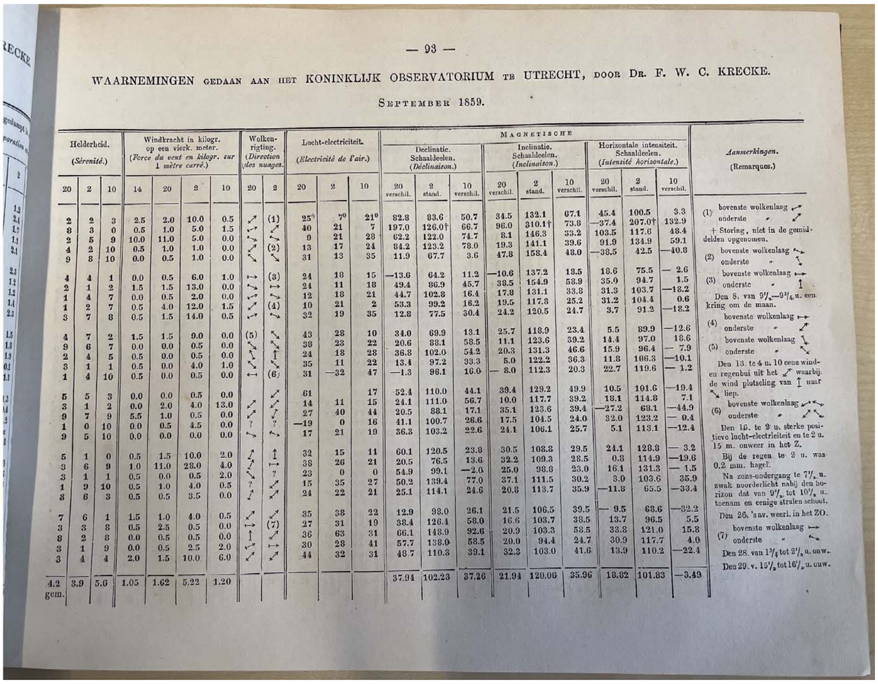
For the variometers in Utrecht only the conversion factor of the declination instrument is provided in the yearbooks: 1 scale part equals 14.957 arcseconds (Koninklijk Nederlandsch Meteorologisch Instituut, 1857, page VI). The conversion factors of the other two instruments had not yet been established, nor are they mentioned in later yearbooks. In Den Helder 1 scale part equals 50 arcseconds for the declination, 36 arcseconds for the inclination and 0.0002 for the horizontal intensity measurements (Koninklijk Nederlandsch Meteorologisch Instituut, 1857, page VI). For the latter no unit is specified but $[\mathrm{mm}^{-1/2}\mathrm{mg}^{1/2}\mathrm{s}^{-1}]$ (i.e. 10^4 nT) is assumed, as it was a customary unit for magnetic field strength at the time (Malin, 1982; Garland, 1979) and gives reasonable results, confirming the correct choice of unit. An alternative interpretation would be that the conversion factor is given in parts of the whole horizontal intensity ($\Delta H/H$). Note that, as discussed in Section 2, the inclination instrument in Den Helder is described to be unreliable due to the continuous change of the magnetic force of the soft iron bars used in the apparatus. A similar warning is given about the instrument that measures the horizontal intensity in Den Helder.

4 Missing conversion factors

One of the reasons why the differences between the 14:00 and 08:00 or 22:00 measurements were listed in the yearbooks instead of the measured values, was because it allows for the easy assessment of the diurnal variation, which is now known to be primarily due to currents in the E-region ionosphere driven by the global thermotidal wind systems (Campbell, 1989). This effect is for example reflected by the zigzag patterns in Figure 3. When the sun is high in the sky (14:00 measurement) the influence of this ionospheric current system is strongest. Comparing the diurnal variation to solar activity (i.e. sunspot number) was a research topic at the time.

Due to the geographical vicinity of the stations in Utrecht and Den Helder (separation of 100 km) the diurnal variation is approximately the same for both locations. This means that the conversion factors from Den Helder can be used in combination with the diurnal variation measurements (i.e. differences between 08:00 and 14:00) to estimate the missing conversion factors of the Utrecht data. In essence, the conversion factors for the horizontal force and inclination that are explicitly given for Den Helder are thus used to calculate the diurnal variations in physical units. The diurnal variations in Utrecht, which are only available in scale parts, are assumed to be the same as both stations are relatively close to each other. By equating the diurnal variation values in physical units and in scale parts, the conversion factors in Utrecht are derived.

Figure 4 shows histograms of the differences between the 08:00 and 14:00 measurements in scale parts during the months



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WAARNEMINGEN GEDAAN AAN HET KONINKLIJK OBSERVATORIUM TE UTRECHT, DOOR DR. F. W. C. KRECKE.

SEPTEMBER 1859.

Helderheid. (*Sérenité.*)			Windkracht in kilogr. op een vierk. meter. (*Force du vent en kilogr. sur 1 mètre carré.*)				Wolken-rigting. (*Direction des nuages.*)		Lucht-electriciteit. (*Electricité de l'air.*)			MAGNETISCHE Declinatie. Schaaldeelen. (*Déclinaison.*)			MAGNETISCHE Inclinatie. Schaaldeelen. (*Inclinaison.*)			MAGNETISCHE Horizontale intensiteit. Schaaldeelen. (*Intensité horizontale.*)		
20	2	10	14	20	2	10	20	2	20	2	10	20 verschil.	2 stand.	10 verschil.	20 verschil.	2 stand.	10 verschil.	20 verschil.	2 stand.	10 verschil.
2	2	3	2.5	2.0	10.0	0.5	↗	(1)	25°	7°	21°	82.8	83.6	50.7	34.5	132.1	67.1	45.4	100.5	3.3
8	3	0	0.5	1.0	5.0	1.5	↗	↗	40	21	7	197.0	126.0†	66.7	96.0	310.1†	73.8	—37.4	207.0†	132.9
2	5	9	10.0	11.0	5.0	0.0	↘	↘	9	21	28	62.2	122.0	74.7	8.1	146.3	33.2	103.5	117.6	48.4
4	2	10	0.5	1.0	1.0	0.0	↗	(2)	13	17	24	84.2	123.2	78.0	19.3	141.1	39.6	91.9	134.9	59.1
9	8	10	0.0	0.5	1.0	0.0	↘	↘	31	13	35	11.9	67.7	3.6	47.8	158.4	48.0	—38.5	42.5	—40.8
4	4	1	0.0	0.5	6.0	1.0	↦	(3)	24	18	15	—13.6	64.2	11.2	—10.6	137.2	13.5	18.6	75.5	— 2.6
2	1	2	1.5	1.5	13.0	0.0	↘	↦	24	11	18	49.4	86.9	45.7	38.5	154.9	58.9	35.0	94.7	1.5
1	4	7	0.0	0.5	2.0	0.0	↗	↘	12	18	21	44.7	102.8	16.4	17.8	131.1	33.8	31.3	103.7	—18.2
1	2	7	0.5	4.0	12.0	1.5	↗	(4)	10	21	2	53.3	99.2	16.2	19.5	117.8	25.2	31.2	104.4	0.6
3	7	8	0.5	1.5	14.0	0.5	↗	↘	32	19	35	12.8	77.5	30.4	24.2	120.5	24.7	3.7	91.2	—18.2
4	7	2	1.5	1.5	9.0	0.0	(5)	↘	43	28	10	34.0	69.9	13.1	25.7	118.9	23.4	5.5	89.9	—12.6
9	6	7	0.0	0.0	0.5	0.0	↘	↘	38	23	22	20.6	88.1	58.5	11.1	123.6	39.2	14.4	97.0	18.6
2	4	5	0.5	0.0	0.5	0.0	↕	↕	24	18	28	36.8	102.0	54.2	20.3	131.3	46.6	15.9	96.4	— 7.9
3	1	1	0.5	0.0	4.0	1.0	↘	↘	35	11	22	13.4	97.2	33.3	5.0	122.2	36.3	11.8	106.3	—10.1
1	4	10	0.5	0.0	0.5	0.0	↤	(6)	31	—32	47	—1.3	96.1	16.0	— 8.0	112.3	20.3	22.7	119.6	— 1.2
5	5	3	0.0	0.0	0.5	0.0		↙	61		17	52.4	110.0	44.1	39.4	129.2	49.9	10.5	101.6	—19.4
3	1	2	0.0	2.0	4.0	13.0	↗	↙	14	11	15	24.1	111.0	56.7	10.0	117.7	39.2	18.1	114.8	7.1
9	7	9	5.5	1.0	0.5	0.0	↗	↙	27	40	44	20.5	88.1	17.1	35.1	123.6	39.4	—27.2	68.1	—44.9
1	0	10	0.0	0.5	4.5	0.0	?	?	—19	0	16	41.1	100.7	26.6	17.5	104.5	24.0	32.0	123.2	— 0.4
9	5	10	0.0	0.0	0.0	0.0	↘	↖	17	21	19	36.3	103.2	22.6	24.1	106.1	25.7	5.1	113.1	—12.4
5	1	0	0.5	1.5	10.0	2.0	↑	↕	32	15	11	60.1	120.5	23.8	30.5	108.8	29.5	24.1	128.8	— 3.2
3	6	9	1.0	11.0	28.0	4.0	↑	↦	38	26	21	20.5	76.5	13.6	32.2	109.3	28.5	0.8	114.9	—19.6
3	1	1	0.5	0.0	0.5	2.0	↘	?	23	0	0	54.9	99.1	—2.0	25.0	98.8	23.0	16.1	131.3	— 1.5
1	9	10	0.5	1.0	4.0	0.5	?	↗	15	35	27	50.2	139.4	77.0	37.1	111.5	30.2	3.0	103.6	35.9
8	6	3	0.5	0.5	3.5	0.0	↑	↗	24	22	21	25.1	114.1	24.6	20.8	113.7	35.9	—11.8	65.5	—33.4
7	6	1	1.5	1.0	4.0	0.5	↗	↗	35	38	22	12.9	98.0	26.1	21.5	106.5	39.5	— 9.5	68.6	—32.2
3	3	8	0.5	2.5	0.5	0.0	↦	(7)	27	31	19	38.4	126.4	58.0	16.6	103.7	38.5	13.7	96.5	5.5
8	2	8	0.0	0.5	0.5	0.0	↕	↗	36	63	31	66.1	148.9	92.6	20.9	103.3	58.5	33.8	121.0	15.8
3	1	9	0.0	0.5	2.5	2.0	↗	↦	30	28	41	57.7	138.0	58.5	20.0	94.4	24.7	30.9	117.7	4.0
3	4	4	2.0	1.5	10.0	6.0	↗	↗	44	32	31	48.7	110.3	39.1	32.3	103.0	41.6	13.9	110.2	—22.4
4.2 gem.	3.9	5.6	1.05	1.62	5.22	1.20						37.94	102.23	37.26	21.94	120.06	35.96	18.82	101.83	—3.49

Aanmerkingen.
(Remarques.)

(1) bovenste wolkenlaag ↗
onderste 〃 ↗

† Storing, niet in de gemiddelden opgenomen.

(2) bovenste wolkenlaag ↘
onderste 〃 ↕

(3) bovenste wolkenlaag ↦
onderste 〃 ↑

Den 8. van 9½—9¾ u. een kring om de maan.

(4) bovenste wolkenlaag ↦
onderste 〃 ↗

(5) bovenste wolkenlaag ↕
onderste 〃 ↘

Den 13. te 4 u. 10 eene wind- en regenbui uit het ↗ waarbij de wind plotseling van ↑ naar ↘ liep.

(6) bovenste wolkenlaag ↗ ↘
onderste 〃 ↗ ↘

Den 16. te 2 u. sterke positieve lucht-electriciteit en te 2 u. 15 m. onweer in het Z.

Bij de regen te 2 u. was 0.2 mm. hagel.

Na zons-ondergang te 7½ u. zwak noorderlicht nabij den horizon dat van 9½ tot 10½ u. toenam en eenige stralen schoot.

Den 26. 's av. weerl. in het ZO.

(7) bovenste wolkenlaag ↦
onderste 〃 ↘

Den 28. van 1¾ tot 2½ u. onw.

Den 29. v. 15½ tot 16½ u. onw.

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Figure 2. Photo of a page of KNMI's 1859 yearbook displaying the geomagnetic measurements made in Utrecht in September. The last three major columns left from the remarks section denote the declination, inclination and horizontal intensity measurements. For each component there are three sub-columns of which the central sub-column lists the observed value at 14:00 in 'schaaldelen' (scale parts). The left and right sub-columns list the differences between the 14:00 values and the morning and evening values respectively.

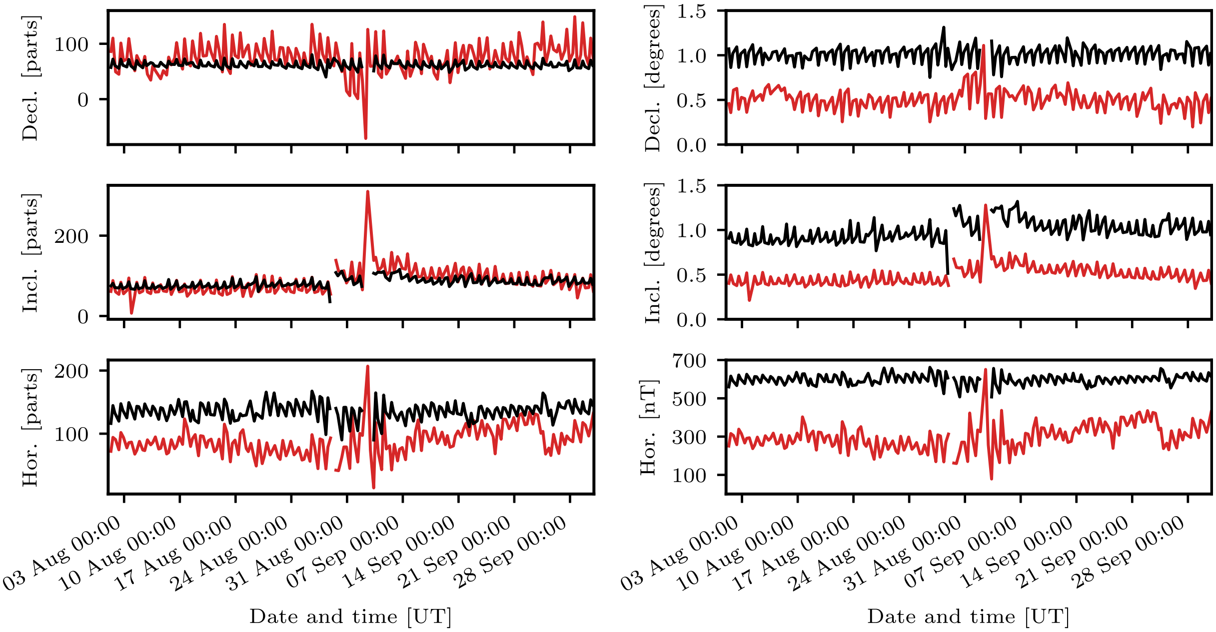

Figure 3. Left: plots of the digitised geomagnetic measurements from August and September 1859. From top to bottom the declination, inclination and horizontal force are shown in scale parts. The red and black lines denote the measurements in Utrecht and Den Helder respectively. Right: the same measurements scaled to modern day units (Sect. 4) with the Den Helder declination and inclination measurements offset to 1 degree (black), and the Utrecht declination and inclination measurements offset to 0.5 degrees (red). The horizontal intensity measurements have been offset to 300 and 600 nT for the Utrecht and Den Helder measurements respectively.

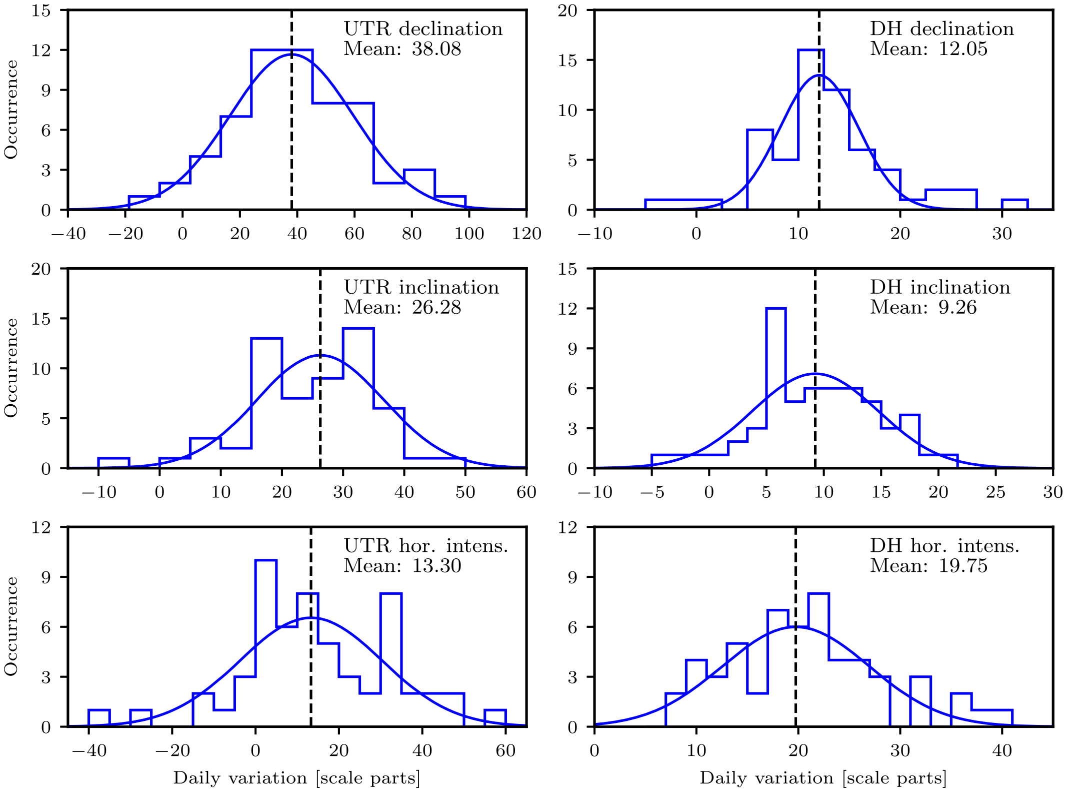

Figure 4. Histograms of the diurnal variations, i.e. the differences between the 08:00 and 14:00 measurements, in scale parts during the months of August and September 1859. From top to bottom the declination, inclination and horizontal intensity are shown, with the Utrecht data on the left, and Den Helder data on the right. Gaussians are fitted to estimate the means (black dashed lines) whose values are listed in the sub-figures.

Table 2. Table listing the diurnal variation of the declination, inclination and horizontal intensity in scale parts and physical units (when scale factors are available) for the Utrecht and Den Helder measurements. The value of 40 nT is based on the assumption that one scale division equals 0.0002 $\mathrm{mm}^{-1/2}\mathrm{mg}^{1/2}\mathrm{s}^{-1}$.

	Utrecht		Den Helder	
	Scale parts	Physical units	Scale parts	Physical units
Declination	38.08	9.5 arcminutes	12.05	10 arcminutes
Inclination	26.28	–	9.26	5.6 arcminutes
Horizontal intensity	13.30	–	19.75	40 nT

of August and September 1859. From top to bottom the declination, inclination and horizontal intensity are shown, with the Utrecht data on the left, and Den Helder data on the right. All histograms are considered to be normally distributed and Gaussians are fitted to estimate the mean values (black dashed lines). Only in case of the declination are both conversion factors for the Utrecht and Den Helder data sets known. The diurnal variations are similar, i.e. 9.5 arcminutes for the Utrecht data and 10 arcminutes for Den Helder. Table 2 lists the mean diurnal variation of the declination, inclination and horizontal intensity in scale parts and physical units for the Utrecht and Den Helder measurements. The missing conversion factors of the Utrecht measurements can now be estimated by dividing the diurnal variation values in physical units by their corresponding values in scale parts (i.e. 40 nT divided by 13.30 and 5.6 arcminutes divided by 26.28). The plots on the right in Figure 3 show the digitised geomagnetic measurements converted to modern units. There seems to be a difference in drift between the Utrecht and Den Helder datasets. It is not possible to reconstruct the cause of this, but perhaps it was caused by temperature variations affecting the measurements.

5 Comparison with Kew and Greenwich magnetograms

Figure 5 shows four panels comparing the variometer declination measurements in the Netherlands to the magnetograms from Greenwich and Kew. From top to bottom the comparisons are: Greenwich (blue line) to Utrecht (red dots), Greenwich (blue line) to Den Helder (black dots), Kew (green line) to Utrecht (red dots) and Kew (green line) to Den Helder (black dots). All variometer measurements have been shifted to match the corresponding magnetograms by subtracting the average

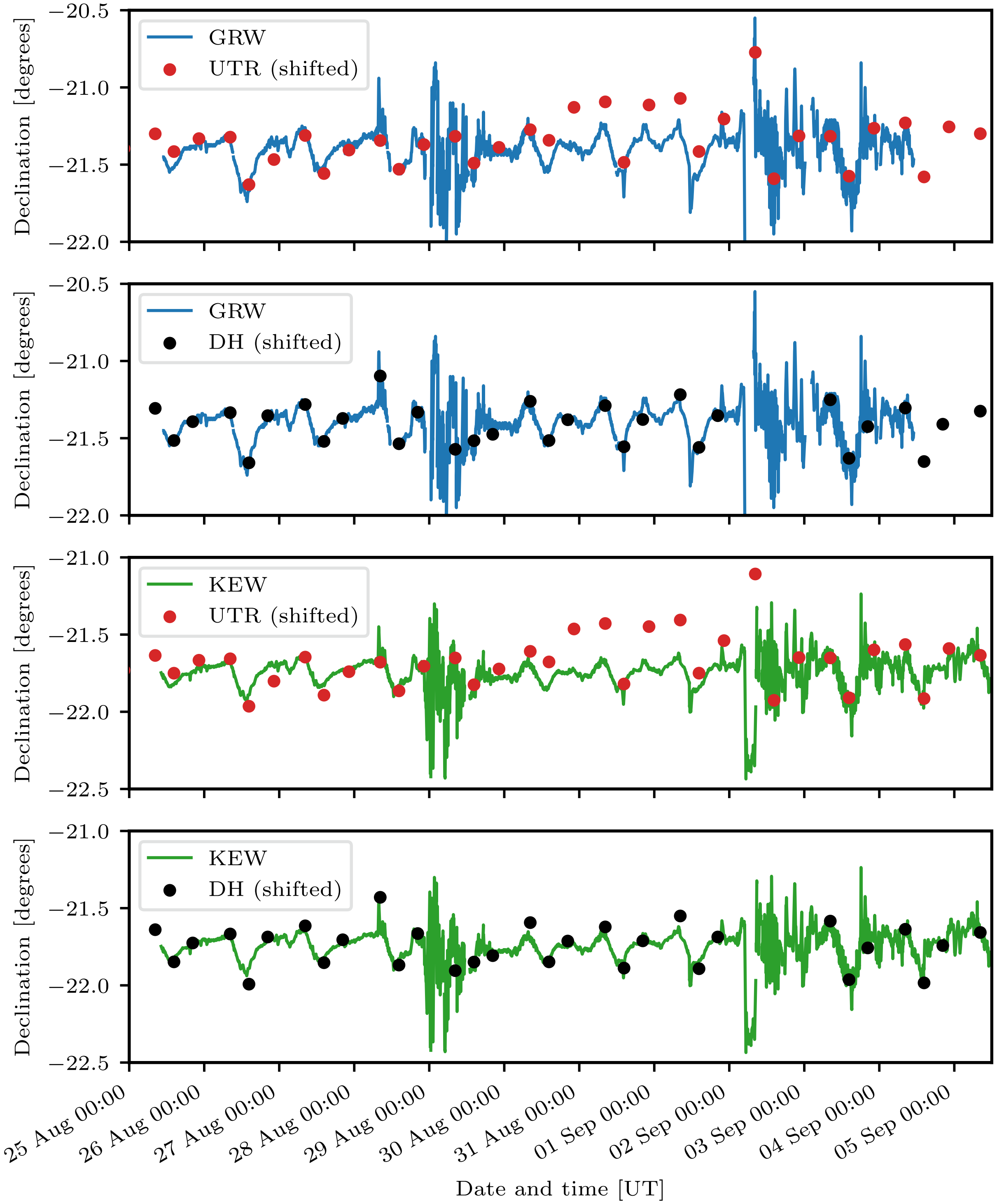

Figure 5. Four panels comparing the variometer declination measurements in the Netherlands to the magnetograms from Greenwich and Kew. From top to bottom the comparisons are: Greenwich (blue line) to Utrecht (red dots), Greenwich (blue line) to Den Helder (black dots), Kew (green line) to Utrecht (red dots) and Kew (green line) to Den Helder (black dots). All variometer measurements have been shifted to match the corresponding magnetograms.

difference between the spot measurements and the magnetogram measurements evaluated at the corresponding spot measurement timestamps. In the case of the Utrecht data only measurements before 30 August are used to match the datasets. Unfortunately, no data points are available during the storm of 2 September. In the period between 30 August and 2 September the spot measurements are significantly off compared to the magnetograms and earlier data points with approximately a quarter of a degree. This discrepancy with respect to earlier observations is also reflected by the data points prior to the

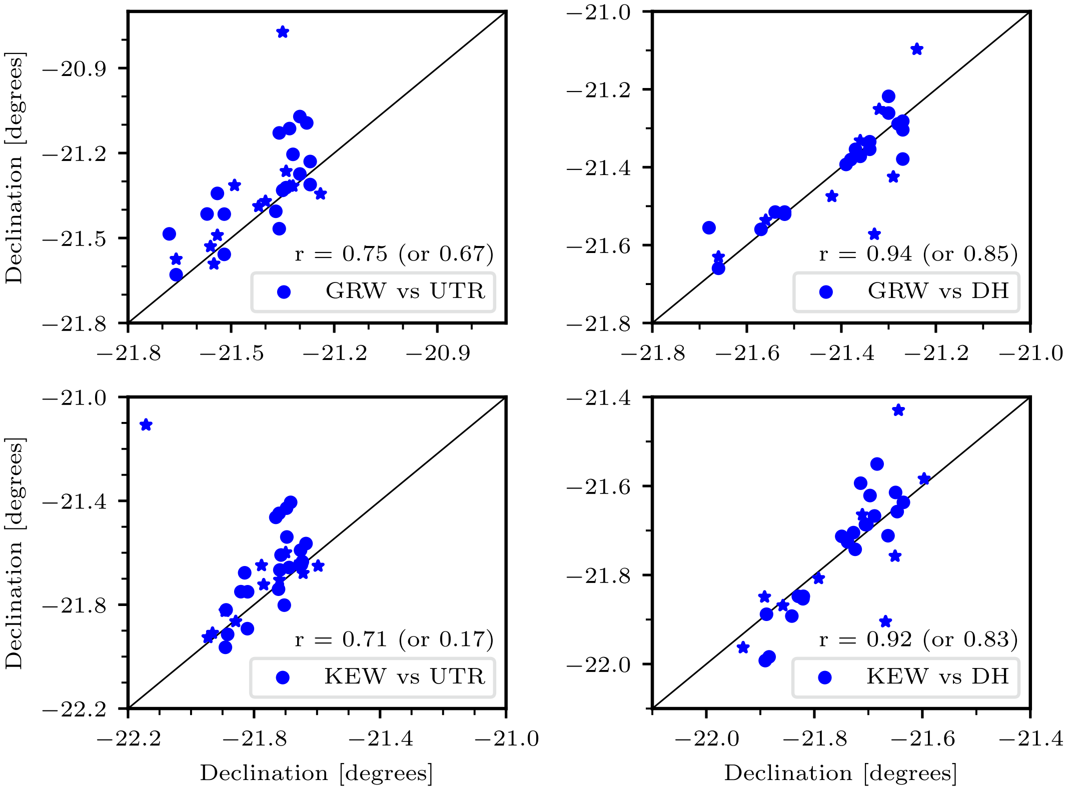

Figure 6. Four panels comparing the variometer declination measurements in the Netherlands to the magnetograms from Greenwich and Kew evaluated at the corresponding variometer timestamps. From left-to-right then top-to-bottom the comparisons are: Greenwich (x-axis) to Utrecht (y-axis), Greenwich (x-axis) to Den Helder (y-axis), Kew (x-axis) to Utrecht (y-axis) and Kew (x-axis) to Den Helder (y-axis). Perfect correlation guidelines are displayed in black. The stars indicate measurements done during the two magnetic storms, i.e. between 28–30 August and 2–4 September. The Pearson correlation coefficients (r) are calculated twice: excluding (dots) and including (dots and stars) the storm measurements. Their values are listed in the sub-figures (including storm measurements denoted between brackets).

strong peak in the upper left panel of Figure 3. It is unknown what caused this inconsistency.

Two distinct peaks in the magnetograms align with the measurements time in the Dutch datasets. The Greenwich magnetogram in the uppermost panel in Figure 5 shows a clear peak during the storm of 2 September which matches well with a higher amplitude data point in the Utrecht measurement. The bottom panel shows another small peak in the Kew magnetogram on 28 August which matches well with the Den Helder measurement.

The correlations between the declination datasets are shown in Figure 6. Note that the same shifts to match the variometer measurements to the corresponding magnetograms (Fig. 5) have been applied. Four panels compare the variometer declination measurements in the Netherlands to the magnetograms from Greenwich and Kew evaluated at the corresponding variometer timestamps. From left-to-right then top-to-bottom the comparisons are: Greenwich (x-axis) to Utrecht (y-axis), Greenwich (x-axis) to Den Helder (y-axis), Kew (x-axis) to Utrecht (y-axis) and Kew (x-axis) to Den Helder (y-axis). Perfect correlation guidelines are displayed in black. The stars indicate measurements during the two magnetic storms, i.e. between 28–30 August and 2–4 September. The Pearson correlation coefficients (r) are calculated twice: excluding (dots) and including (dots and stars) the storm measurements. Their values are listed in the sub-figures (including storm measurements denoted between brackets). This distinction is made because during storm periods the declination changes more rapidly than the available timing precision. For example, the declination peak in the Greenwich magnetogram on 2 September (top panel in Fig. 5) deviates from the Utrecht measurement by 0.58 degrees. If the Utrecht measurement time was chosen 2 min earlier, this difference would be 0.08 degrees. From the yearbooks it is unclear how long it took to make the observations, in what order the three instruments were read out and with what time accuracy the observation procedures were carried out. The non-storm correlation coefficients indicate a very strong correlation between the Den Helder measurements and both magnetograms; the values are 0.94 and 0.92 for Greenwich and Kew respectively. Also for the Utrecht measurements there is generally a good correlation with values of 0.75 for Greenwich and 0.71 for Kew.

Similar comparisons for the horizontal intensity are shown in Figures 7 and 8. The four panels have the same configuration and colour use as Figures 5 and 6. Also here the spot measurements have been matched to the magnetograms using the same technique. For the Den Helder data the correlation with both magnetograms is good with non-storm correlation coefficients of 0.82 and 0.89 for Greenwich and Kew respectively. Unfortunately, during both storms on 29 August and 2 September no values are listed in the yearbooks. The observations from

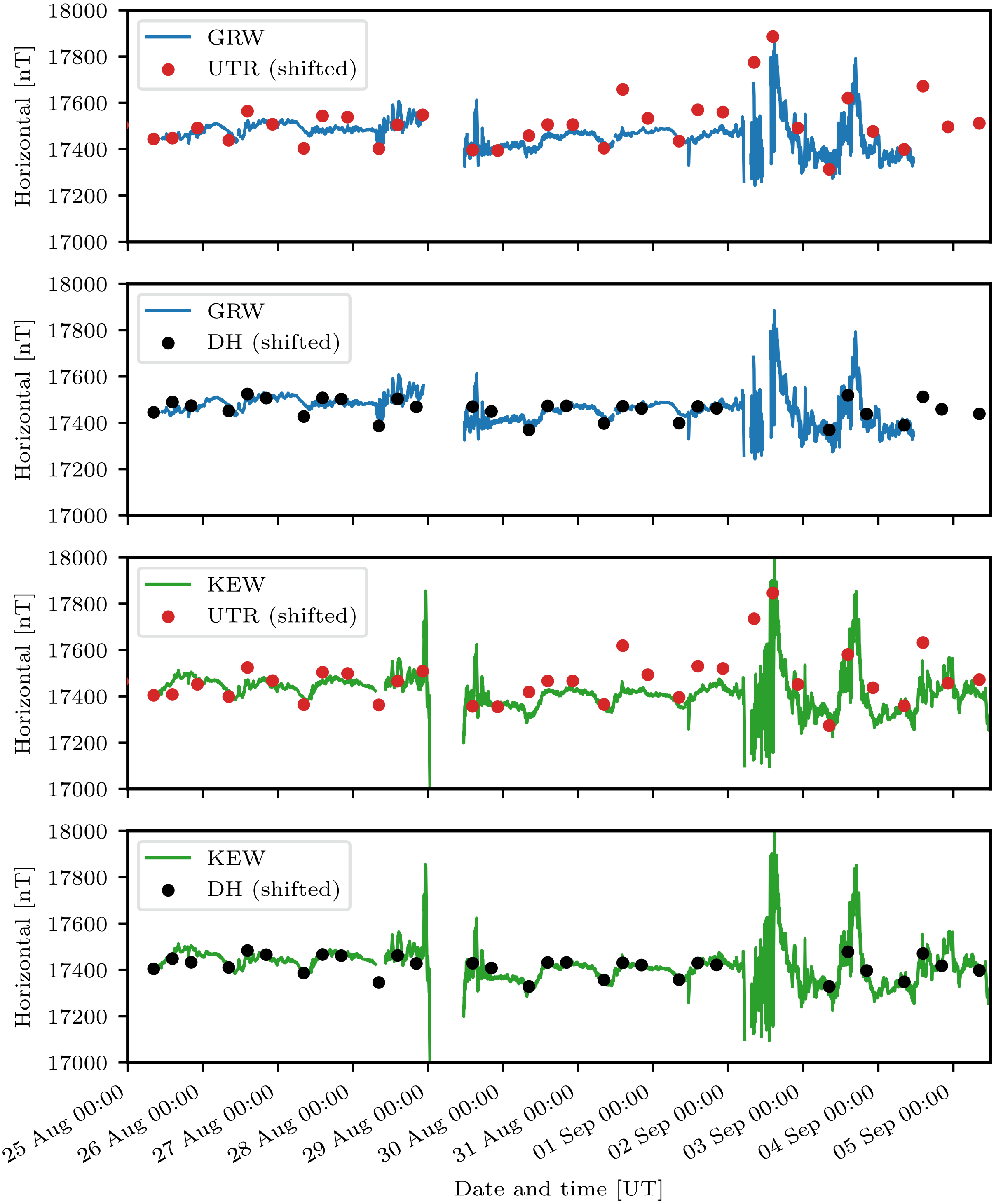

Figure 7. Four panels comparing the horizontal intensity measurements in the Netherlands to the magnetograms from Greenwich and Kew. From top to bottom the comparisons are: Greenwich (blue line) to Utrecht (red dots), Greenwich (blue line) to Den Helder (black dots), Kew (green line) to Utrecht (red dots) and Kew (green line) to Den Helder (black dots). All variometer measurements have been shifted to match the corresponding magnetograms.

Utrecht correspond less well, although there is general agreement between the values (non-storm correlation coefficients of 0.58 for Greenwich and 0.48 for Kew). The peak data point during the storm of 2 September matches the magnetogram values well. Also for the Utrecht data set no observations are available on 29 August. Again, in the period between 30 August and 2 September there is a discrepancy between the Utrecht data, and the magnetograms and earlier data points. The difference is about 100 nT. The general agreement between the magnetograms and Den Helder data seems to suggest that the warning

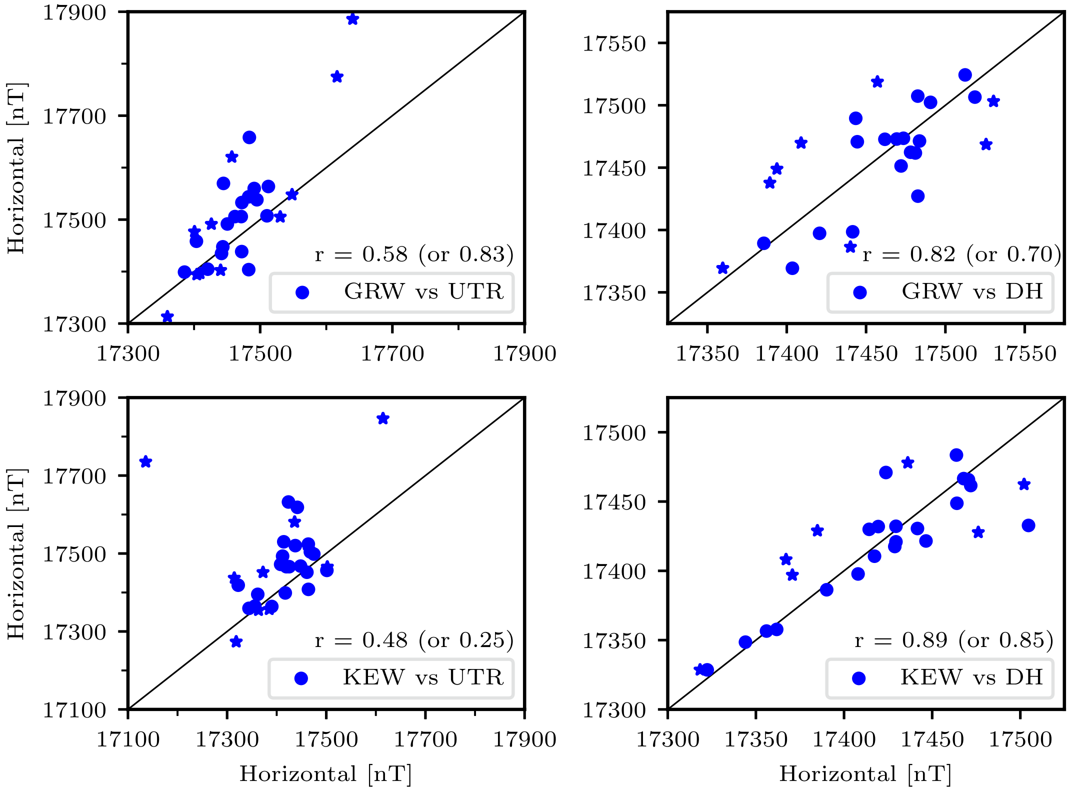

Figure 8. Four panels comparing the variometer horizontal intensity measurements in the Netherlands to the magnetograms from Greenwich and Kew evaluated at the corresponding variometer timestamps. From left-to-right then top-to-bottom the comparisons are: Greenwich (x-axis) to Utrecht (y-axis), Greenwich (x-axis) to Den Helder (y-axis), Kew (x-axis) to Utrecht (y-axis) and Kew (x-axis) to Den Helder (y-axis). Perfect correlation guidelines are displayed in black. The stars indicate measurements done during the two magnetic storms, i.e. between 28–30 August and 2–4 September. The Pearson correlation coefficients (r) are calculated twice: excluding (dots) and including (dots and stars) the storm measurements. Their values are listed in the sub-figures (including storm measurements denoted between brackets).

about the reliability of the horizontal intensity measurements in the yearbook was overly cautious.

Finally, the comparisons between the inclination measurements are shown in Figure 9, again with the same ordering as used in Figure 5. Also here shifts have been applied to match the magnetograms. The inclination measurements of Kew and Greenwich are calculated using the horizontal (H) and vertical (Z) components as follows:

$$I = \arctan\left(\frac{Z}{H}\right) \tag{13}$$

The original Greenwich vertical trace is largely missing. Furthermore, in Beggan et al. (2024) it is argued that vertical component is too large and is not a true record of the magnetic field change. For completeness the Greenwich comparisons are still shown (upper two graphs in Fig. 9). Despite the overestimated Greenwich Z-component the inclination measurements of Greenwich and Kew are of similar magnitude. This is because of the dampening effect of the arctan function (e.g. if Z = 44,500 nT and H = 17,500 nT a 20% increase in Z becomes a 4.8% increase in I). Contrary to the declination and horizontal intensity there seems to be very little correlation between the Dutch and London inclination data. This is in accord with the warning about the unreliability given in the yearbooks. Moreover, as there is a generally accepted assumption that the magnetic fields generated by the induced currents in the conductive ground play an essential role in the variations of the vertical intensity, the difference could also partly be attributed to a different subsurface conductivity distribution.

6 Summary and conclusion

The Royal Netherlands Meteorological Institute (KNMI) has a long history in the field of geomagnetic measurements. Geomagnetic observations captured in Utrecht and Den Helder during the Carrington event are digitised from KNMI's yearbook of 1859, and compared to magnetograms taken in Kew and Greenwich. Cross-checking these datasets is useful to independently corroborate the scaling techniques used in the digitisation of the London magnetograms, and to assess whether historical data obtained in the United Kingdom could be used for studies on the impact of geomagnetic storms in the Netherlands.

The records in the yearbooks are listed in scale parts. For the variometers in Utrecht only the conversion factor of the declination instrument is known. The definite conversion factors of the other two instruments had not yet been established, nor are they mentioned in later yearbooks. The conversion factors from Den Helder have been used in combination with the diurnal variation

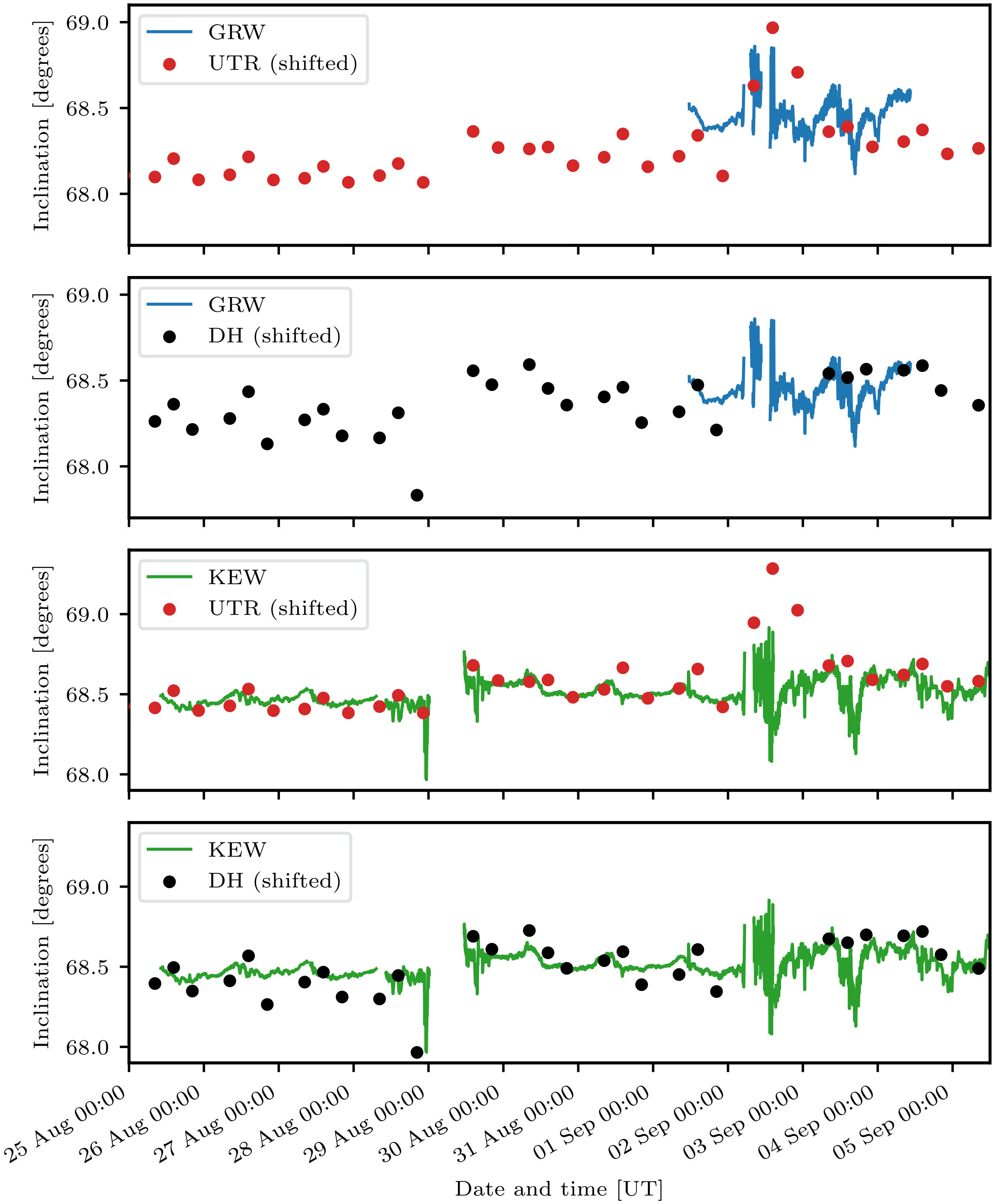

Figure 9. Four panels comparing the variometer inclination measurements in the Netherlands to the magnetograms from Greenwich and Kew. From top to bottom the comparisons are: Greenwich (blue line) to Utrecht (red dots), Greenwich (blue line) to Den Helder (black dots), Kew (green line) to Utrecht (red dots) and Kew (green line) to Den Helder (black dots). All variometer measurements have been shifted to match the corresponding magnetograms.

measurements to estimate the missing conversion factors of the Utrecht data.

Especially for the Den Helder declination measurements there is a strong correlation with both London magnetograms; the non-storm correlation coefficients are 0.94 and 0.92 for Greenwich and Kew respectively. During storm periods the available timing precision of the Dutch data is the dominant source of uncertainty when comparing with the magnetograms. Also for the Utrecht declination measurements there is generally a good correlation with the Greenwich (r = 0.75) and

Kew (r = 0.71) observations outside storm time. This is despite the significant quiet-time differences of about a quarter of a degree in the period between 30 August and 2 September.

For the Den Helder horizontal intensity measurements the correlation with both magnetograms is good with non-storm correlation coefficients of 0.82 and 0.89 for Greenwich and Kew respectively. Unfortunately, during both storms on 29 August and 2 September almost no values are listed in the yearbooks. The observations from Utrecht match less well, although there is general agreement between the values (non-storm correlation coefficients of 0.58 for Greenwich and 0.48 for Kew). Note that in the period between 30 August and 2 September there are significant quiet-time differences of about 100 nT. The inclination measurements from Utrecht and Den Helder do not match the Greenwich or Kew data, possibly due to a different subsurface conductivity distribution or the instruments not working correctly.

Despite the limited number of data points during the two storm periods in August and September 1859, it is plausible to assume that the storm time declination and horizontal intensity observations accurately describe the state of the then-prevailing magnetic field in the Netherlands, as the magnetometer data from Kew and Greenwich are of similar magnitude at those measurement times. Also during the more quiet periods there is good agreement between spot measurements and magnetograms. The point measurements from the Netherlands do not provide information on shorter time scales, however the amplitude of differences between nearby stations at varying distances close to auroral currents have been systematically studied using modern minute-mean observations at higher latitudes by Beggan et al. (2018). The coherent registration of these features at lower latitude during a larger storm therefore suggests that such a level of agreement between the conditions in the United Kingdom and the Netherlands may well also be valid on timescales shorter than the three times per day cadence. This helps to justify using the high-cadence London measurements as the best available observations for future investigations into the risk of extreme space weather during a Carrington-like event for the Netherlands.

Further research is needed to investigate whether this coherence holds during the Carrington storm conditions on the minute timescale used in dB/dt analyses. KNMI's archives contain magnetograms starting from 1892. Digitisation of these magnetograms recorded during later strong geomagnetic storms, and comparing them to contemporary magnetograms from England, will be beneficial for studying coherence under major storm conditions at these lower latitudes.

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We kindly thank Daphne Cupido and Jeanine Borst for their help with locating and accessing KNMI's historical geomagnetic records. We also thank the anonymous reviewers and editor for their feedback, which significantly improved the quality of this manuscript. The editor thanks Hisashi Hayakawa and two anonymous reviewers for their assistance in evaluating this paper.

Data availability statement

The digitised data from the yearbooks, as well as the derived data, can be found in csv files in the Supplementary materials attached to this paper. The programming code used in the analysis, and the excerpts describing the instrumentation can be found there as well. The analysis has been done in the programming language Python with the help of the Numpy, Pandas and Matplotlib libraries.

Supplementary material

The supplementary materials of this article are available at https://www.swsc-journal.org/10.1051/swsc/2025003/olm.

Supplementary material 1: Excerpts from historical (year)books describing the Dutch geomagnetic observations with English translations.

Supplementary material 2: A zip file containing the Python code used for the analysis and the data files. A readme text file enclosed in the zip file explains the contents and origin of the data files.

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