Figure 1.

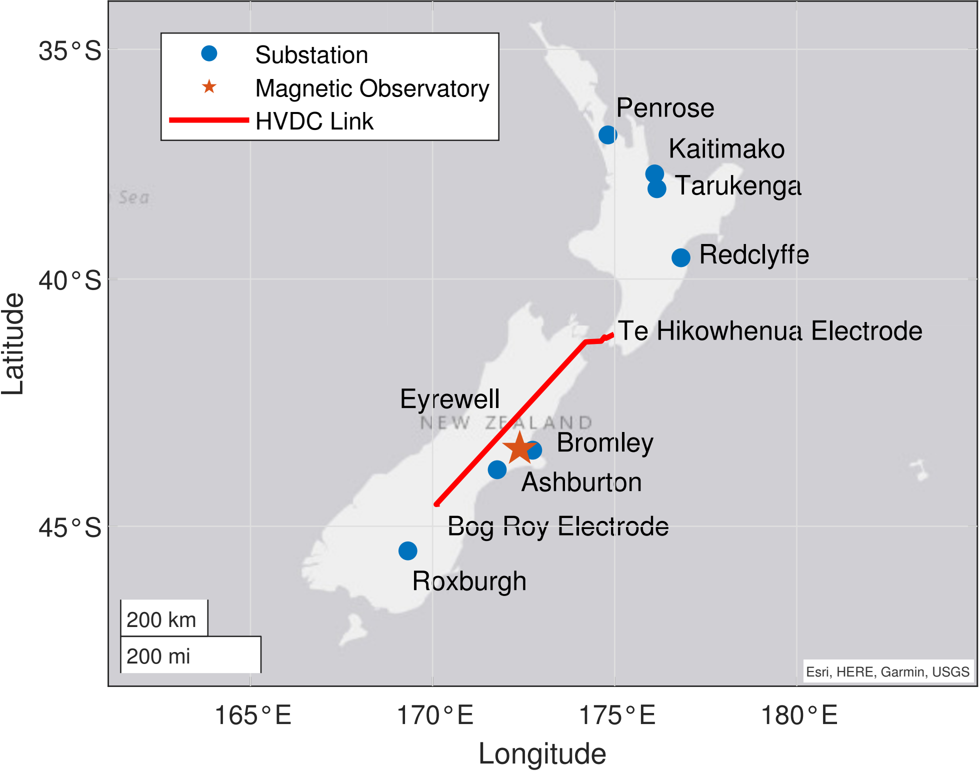
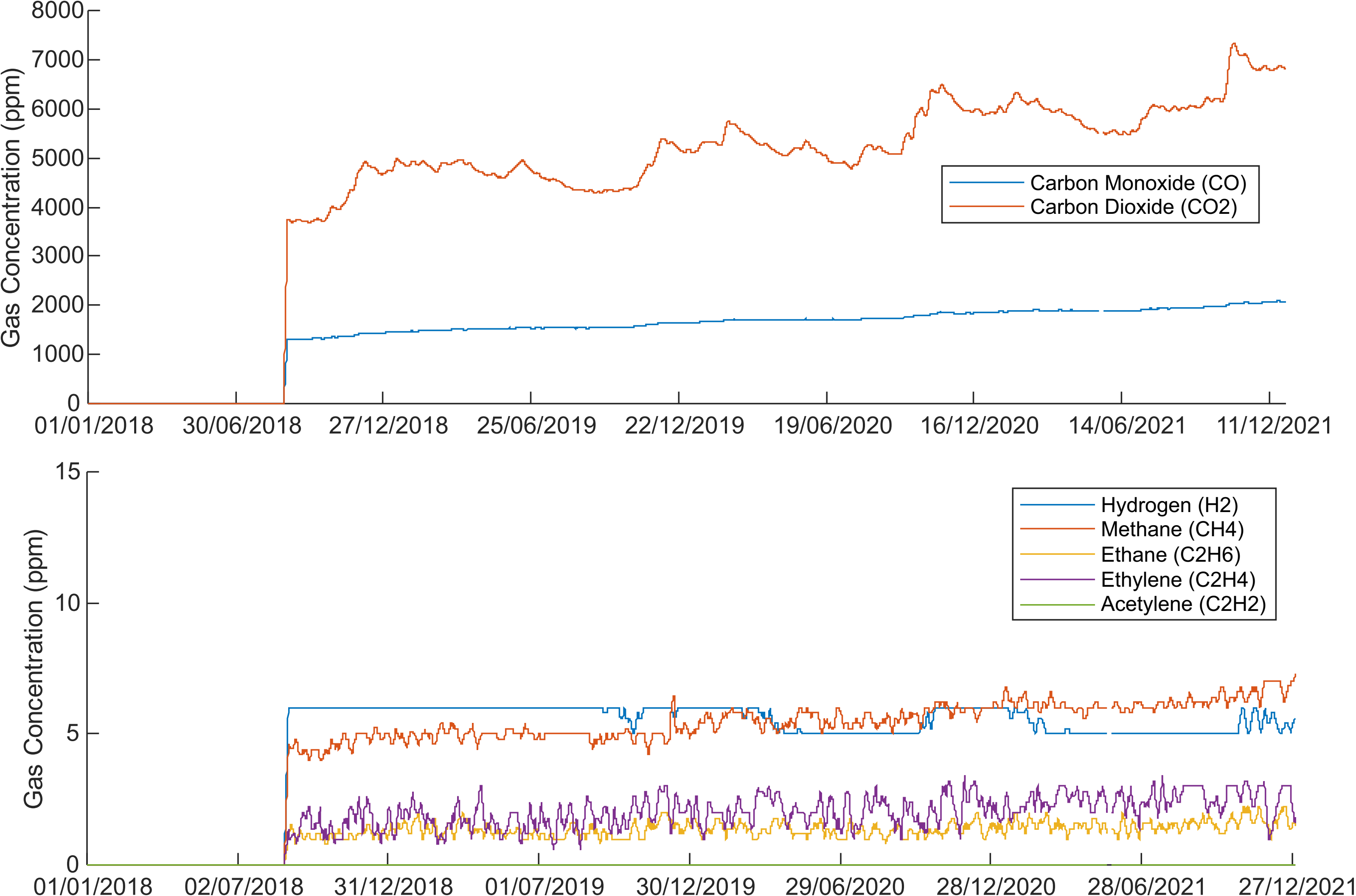
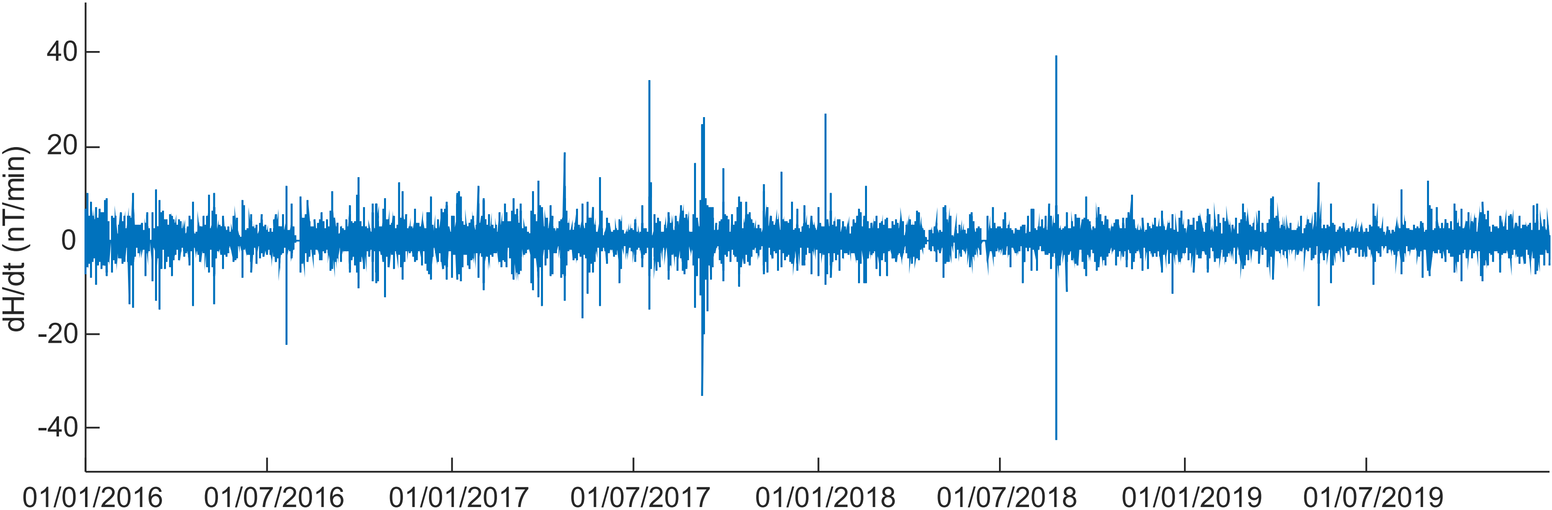

Substation
Magnetic Observatory
HVDC Link
Penrose
Kaitimako
Tarukenga
Redclyffe
Te Hikowhenua Electrode
Eyrewell
NEW ZEALAND
Bromley
Ashburton
Bog Roy Electrode
Roxburgh
Sea
200 km
200 mi
Esri, HERE, Garmin, USGS
35°S
40°S
45°S
165°E
170°E
175°E
180°E
Latitude
Longitude

Figure 2.



Gas Concentration (ppm)
8000
7000
6000
5000
4000
3000
2000
1000
0
01/01/2018
30/06/2018
27/12/2018
25/06/2019
22/12/2019
19/06/2020
16/12/2020
14/06/2021
11/12/2021
Carbon Monoxide (CO)
Carbon Dioxide (CO2)
Gas Concentration (ppm)
15
10
5
0
01/01/2018
02/07/2018
31/12/2018
01/07/2019
30/12/2019
29/06/2020
28/12/2020
28/06/2021
27/12/2021
Hydrogen (H2)
Methane (CH4)
Ethane (C2H6)
Ethylene (C2H4)
Acetylene (C2H2)

Figure 3.



dH/dt (nT/min)
40
20
0
-20
-40
01/01/2016
01/07/2016
01/01/2017
01/07/2017
01/01/2018
01/07/2018
01/01/2019
01/07/2019

Figure 4.

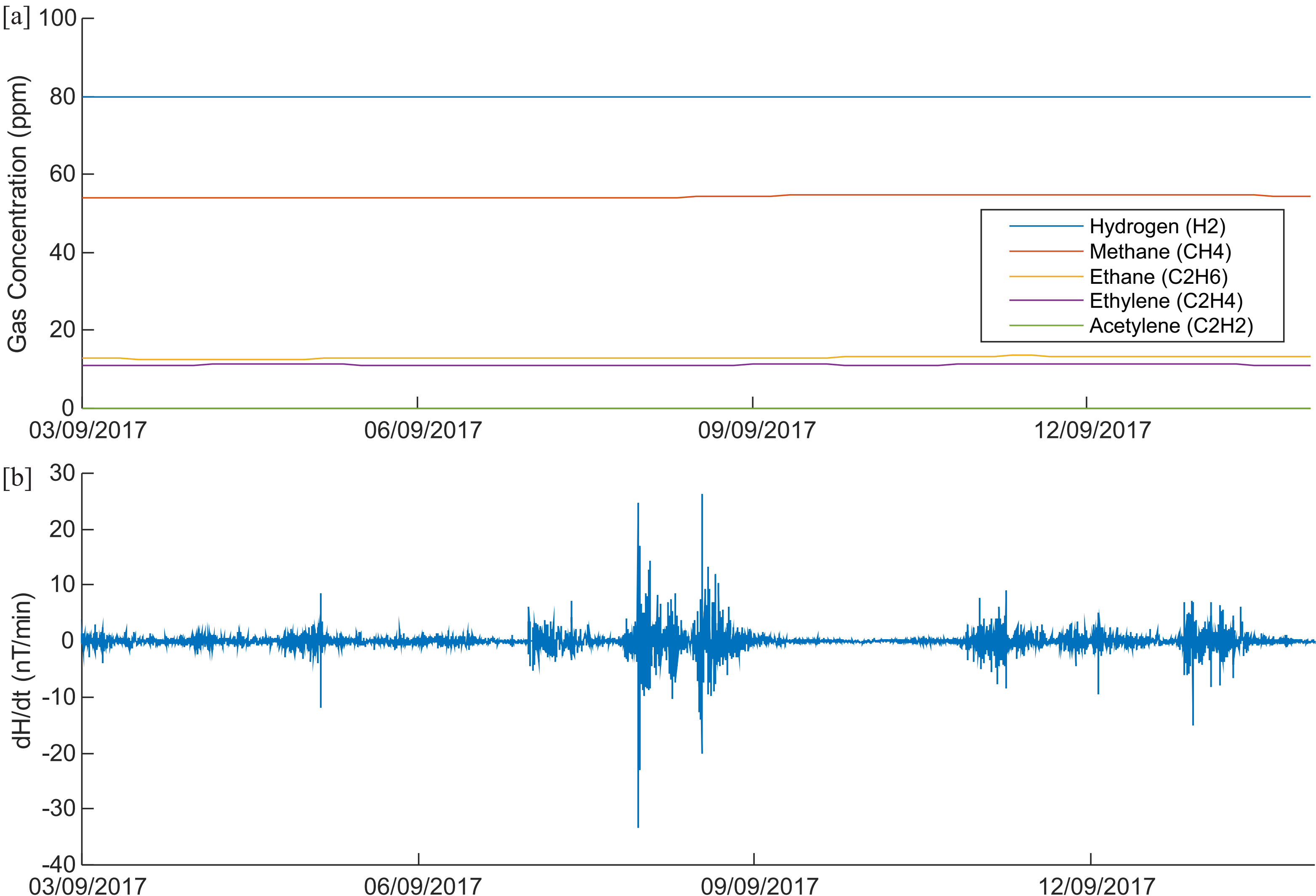
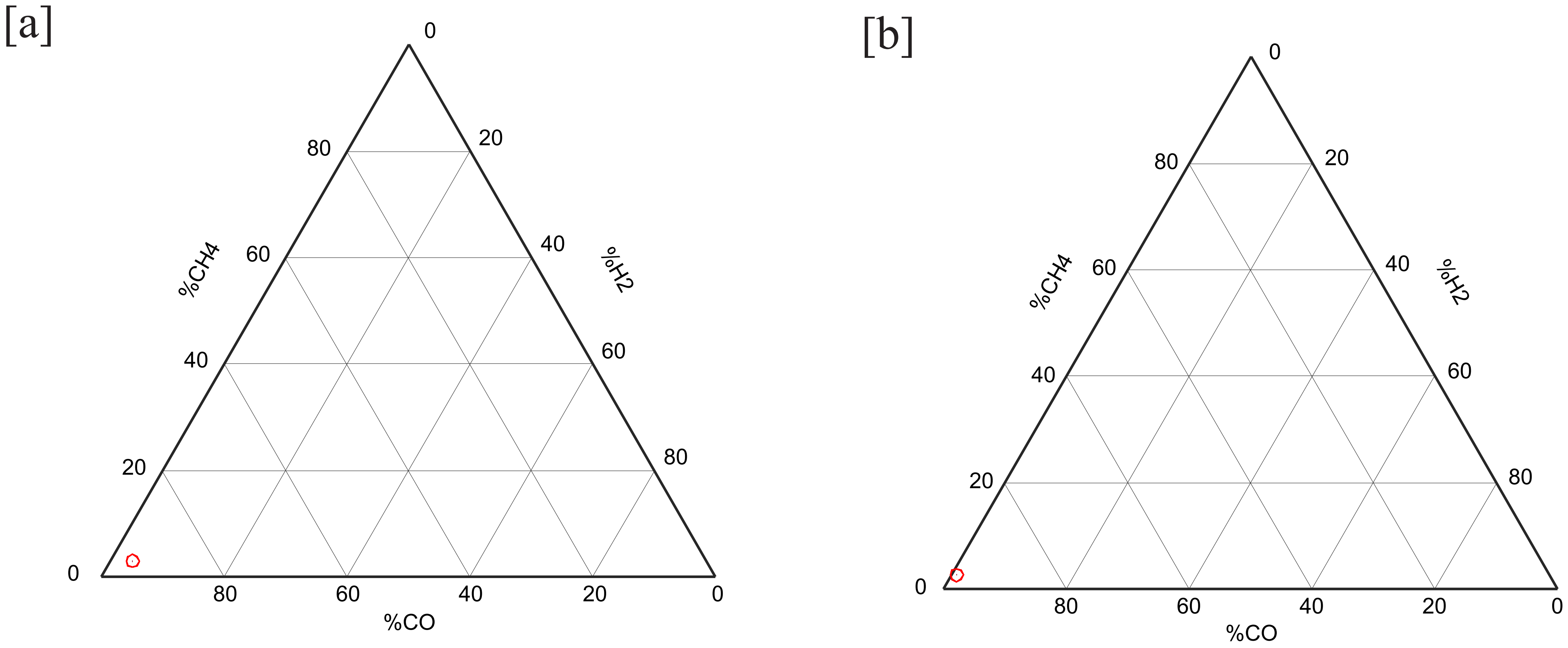

[a]
Gas Concentration (ppm)
100
80
60
40
20
0
03/09/2017
06/09/2017
09/09/2017
12/09/2017
Hydrogen (H2)
Methane (CH4)
Ethane (C2H6)
Ethylene (C2H4)
Acetylene (C2H2)
[b]
dH/dt (nT/min)
30
20
10
0
-10
-20
-30
-40
03/09/2017
06/09/2017
09/09/2017
12/09/2017

Figure 5.



[a]
0
20
40
60
80
%CH4
%H2
%CO
[b]
0
20
40
60
80
%CH4
%H2
%CO

Figure 6.

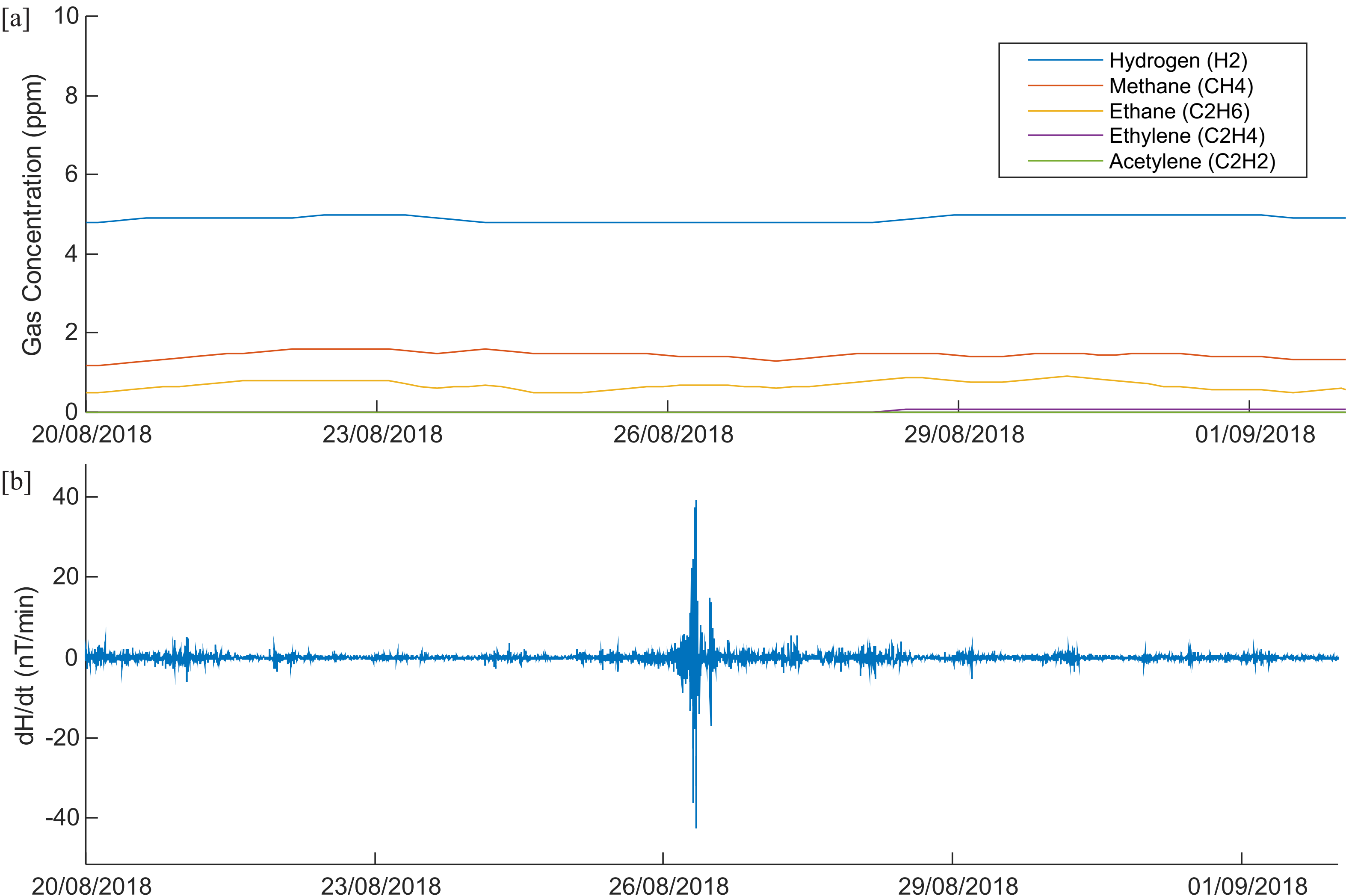

[a]
Gas Concentration (ppm)
Hydrogen (H2)
Methane (CH4)
Ethane (C2H6)
Ethylene (C2H4)
Acetylene (C2H2)
10
8
6
4
2
0
20/08/2018
23/08/2018
26/08/2018
29/08/2018
01/09/2018
[b]
dH/dt (nT/min)
40
20
0
-20
-40
20/08/2018
23/08/2018
26/08/2018
29/08/2018
01/09/2018

Figure 7.

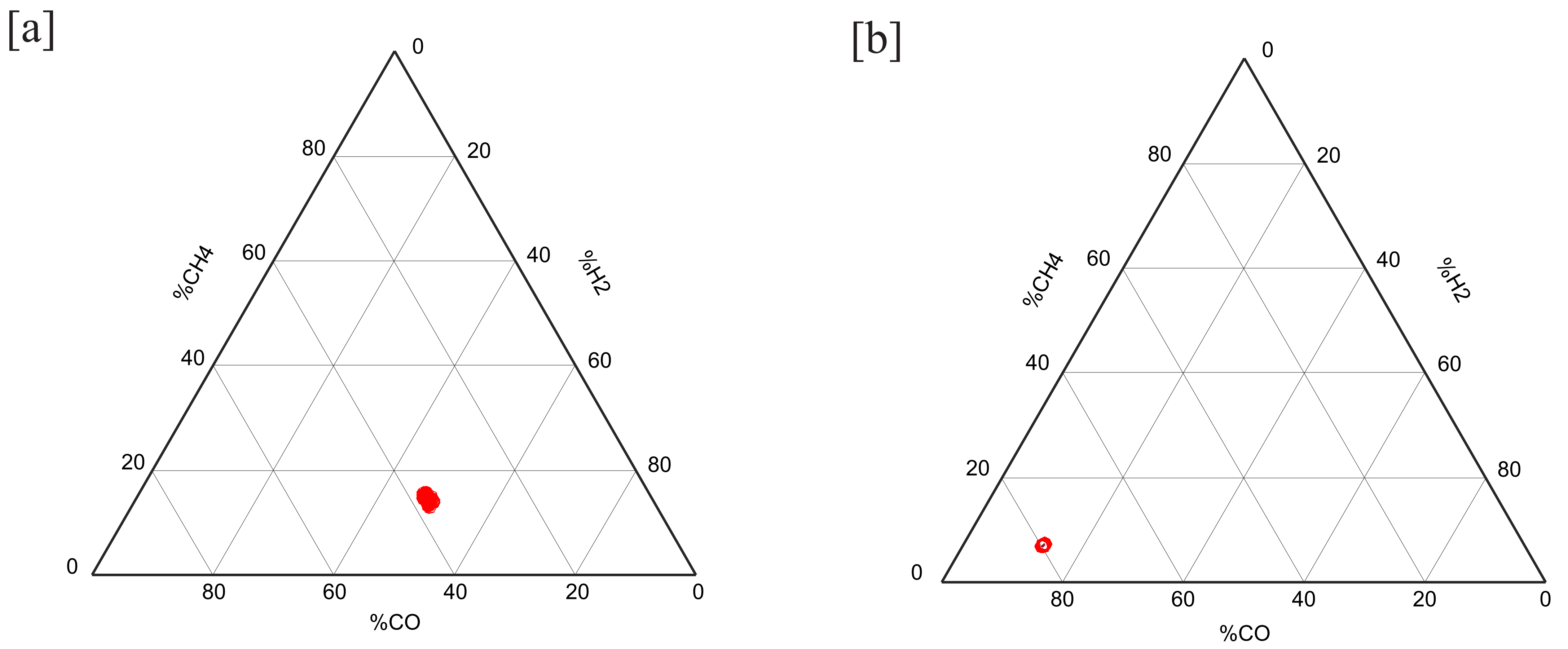

[a]
[b]
%CH4
%H2
%CO
0
20
40
60
80

Figure 8.

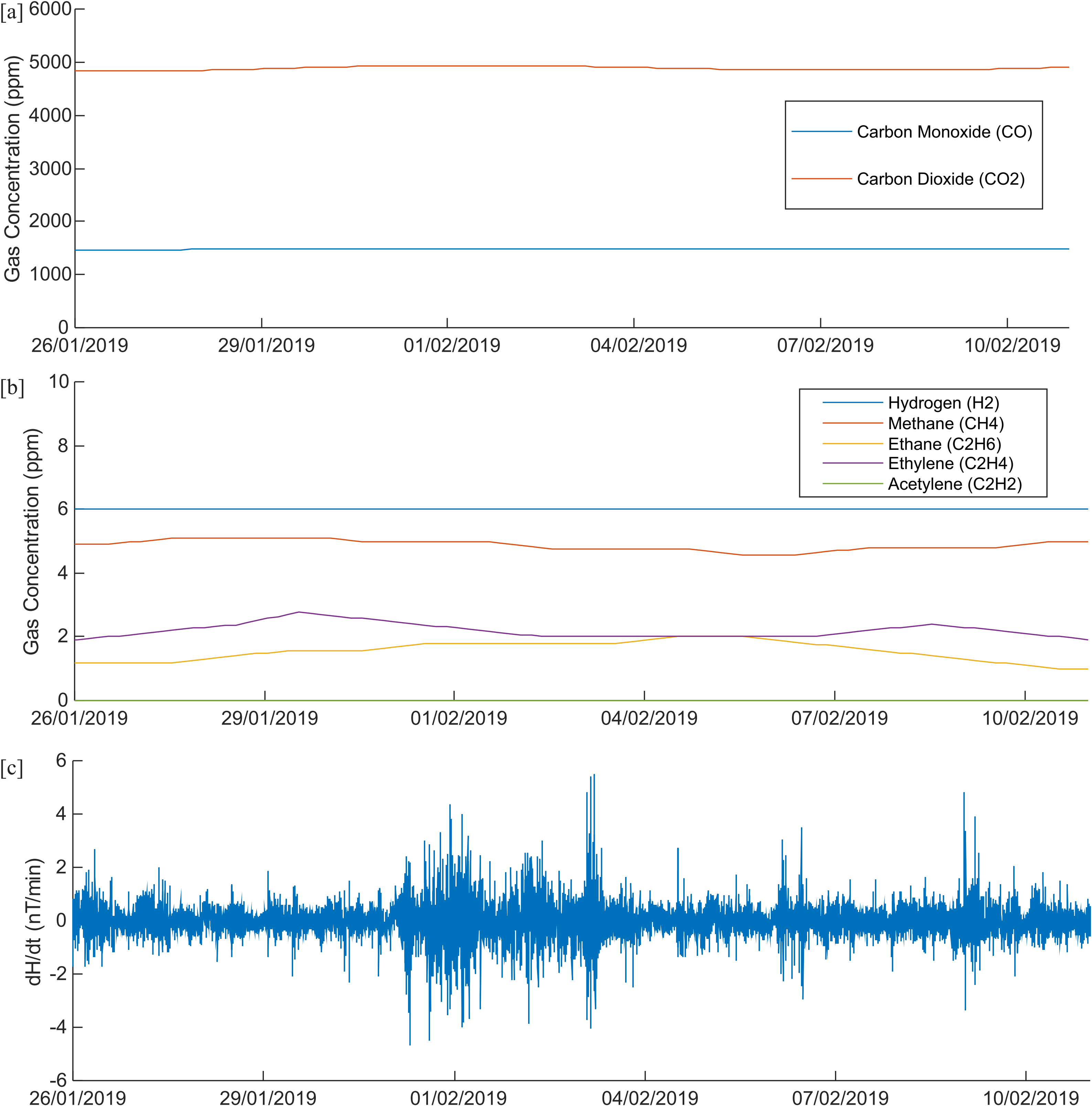
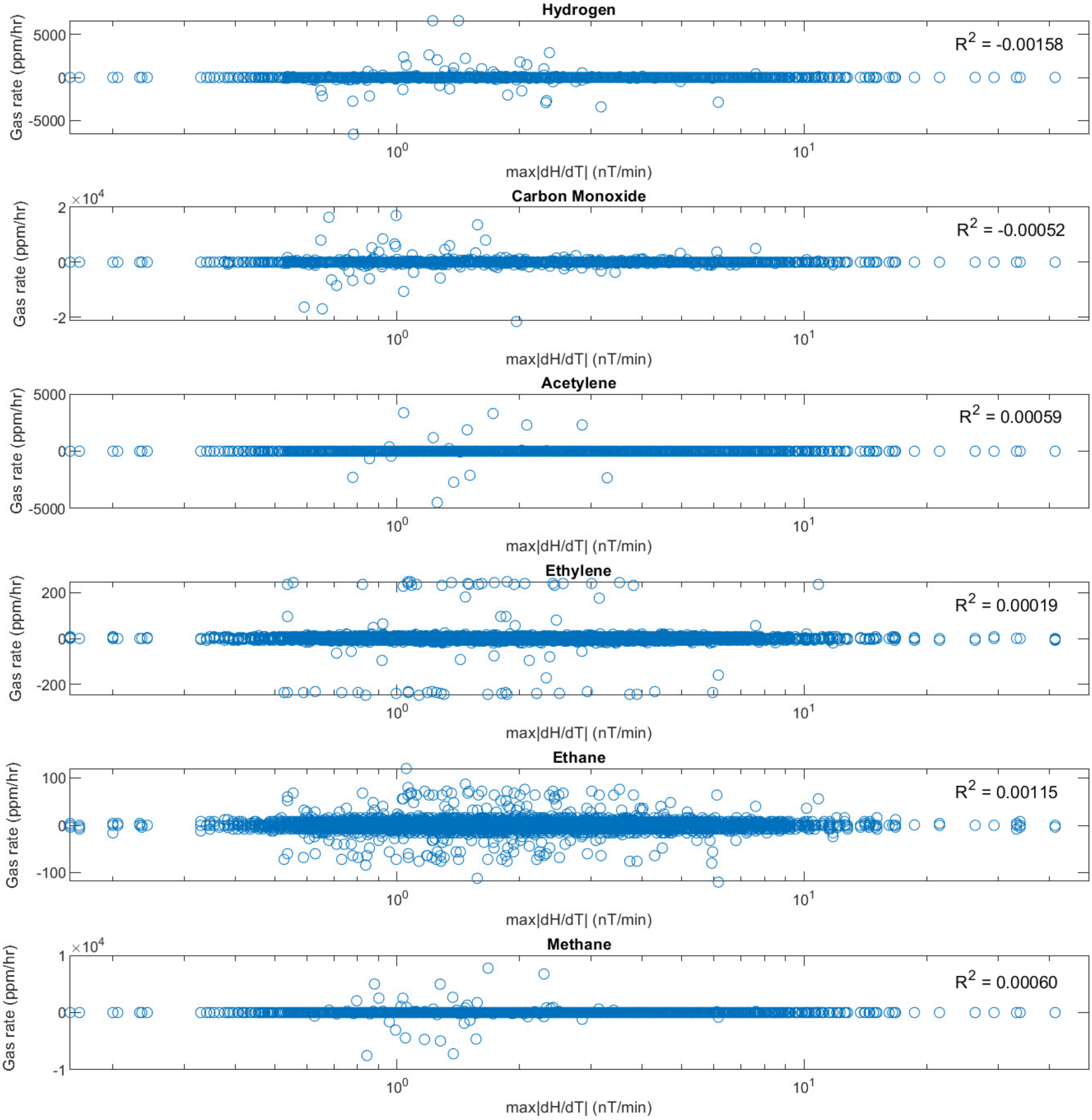
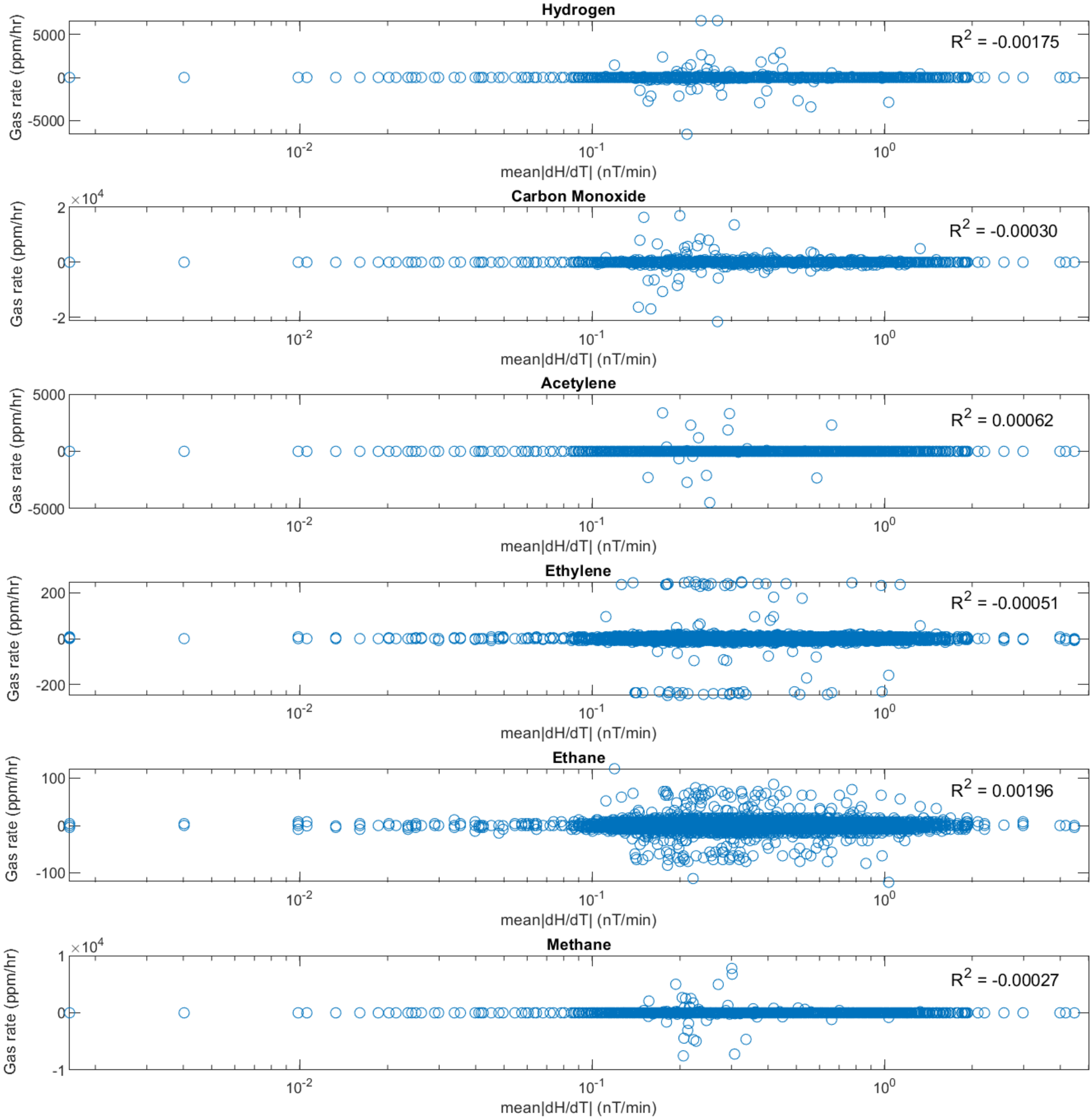

[a]
Gas Concentration (ppm)
Carbon Monoxide (CO)
Carbon Dioxide (CO2)
26/01/2019
29/01/2019
01/02/2019
04/02/2019
07/02/2019
10/02/2019
[b]
Gas Concentration (ppm)
Hydrogen (H2)
Methane (CH4)
Ethane (C2H6)
Ethylene (C2H4)
Acetylene (C2H2)
[c]
dH/dt (nT/min)

Figure 9.



Hydrogen
Gas rate (ppm/hr)
5000
0
-5000
10^0
10^1
max|dH/dT| (nT/min)
R^2 = -0.00158
Carbon Monoxide
$\times 10^4$
2
0
-2
R^2 = -0.00052
Acetylene
R^2 = 0.00059
Ethylene
200
-200
R^2 = 0.00019
Ethane
100
-100
R^2 = 0.00115
Methane
1
-1
R^2 = 0.00060

Figure 10.


Hydrogen
Gas rate (ppm/hr)
5000
0
-5000
R^2 = -0.00175
10^-2
10^-1
10^0
mean|dH/dT| (nT/min)
Carbon Monoxide
×10^4
2
0
-2
R^2 = -0.00030
Acetylene
R^2 = 0.00062
Ethylene
200
-200
R^2 = -0.00051
Ethane
100
-100
R^2 = 0.00196
Methane
1
-1
R^2 = -0.00027

Assessment of Space Weather Impacts on New Zealand Power Transformers using Dissolved Gas Analysis

S. P. Subritzky[1], A.C. Lapthorn[1], S. Hardie[1], D.H. Mac Manus[2], C. J. Rodger[2], M. Dalzell[3]

[1]Department of Electrical and Computer Engineering, University of Canterbury, Christchurch, New Zealand.

[2]Department of Physics, University of Otago, Dunedin, New Zealand.

[3]Transpower New Zealand Limited

Corresponding author: Soren Subritzky (soren.subritzky@pg.canterbury.ac.nz)

Key Points:

- Gas data from eight NZ transformers from 2016-2019 were analysed to relate geomagnetic activity with the production of combustible gasses.
- A statistical investigation was conducted analysing gas records alongside magnetic field and current measurements over the same period.
- No link found between combustible gas production in these transformers and geomagnetic activity for this time period.

Abstract

Space weather can have major impacts on electrical infrastructure. Multiple instances of transformer damage have been attributed to geomagnetic storms in recent decades, for example, the Hydro Quebec incident of 1989 and the November 2001 storm in New Zealand. While many studies exist on the impacts of geomagnetic storms on power transformers in New Zealand, no studies exist that employ Dissolved Gas Analysis (DGA) techniques to relate geomagnetic storms to transformer gassing. A relationship has been reported between geomagnetic activity and DGA for South Africa, while none was found in a recent study in Great Britain. This paper attempts to examine this research question by examining dissolved gas data across eight power transformers in different substations in New Zealand from 2016 to 2019. Case studies were conducted which analysed the DGA readings of each transformer alongside horizontal magnetic field component rate of change measurements at Eyrewell across six geomagnetic storms. These case studies were then augmented with an analysis of the entire dataset where magnetic field measurements were compared with individual gas rates to establish a correlation between gas production and geomagnetic activity. Analysis of the results of this study concluded that no link had been found between the production of combustible gasses in a transformer and geomagnetic activity during the observation period. However, we note our dissolved gas analysis was largely in a geomagnetically quieter period, which may limit our analysis. The production of combustible gasses is not correlated to geomagnetic storms for the time period and transformers analysed.

Plain Language Summary

Space weather (changes in the Earth's magnetic field due to changes in the suns atmosphere) is well known to have major impacts on electrical infrastructure. Multiple incidents have been observed over recent decades which have been directly linked to space weather events, for example the Hydro Quebec incident of 1989 and the November 2001 storm in New Zealand. In this study the impacts of space weather on power station transformers in New Zealand was analysed. Data on transformer health for eight different transformers was compared to magnetic field activity from 2016 to 2019 to look for evidence of transformer damage due to solar storms. Case studies were analysed across six different storms using dissolved gas analysis, which looks at the gas levels inside a transformer to determine its condition. Following the case studies general trends in the data were analysed. From our analysis we concluded that no link had been found between space weather and transformer damage during the observation period. This was likely due to the quiet nature of the sun's atmosphere at the time.

1 Introduction

Power transformers play a crucial role in AC power transmission systems. Outages of power transformers can significantly impact electricity supply, causing regional outages or even full-scale blackouts. Studies by Ferguson et al. (2000) found a strong correlation between electricity use and wealth creation; therefore, it is apparent that maintaining a stable supply is critical for modern society.

Geomagnetically Induced Currents (GICs) arise from space weather and can flow in the Earth's surface. These currents are quasi-DC in nature, with frequencies ranging from 0.1mHz to 1Hz (Pulkkinen, 2003). These quasi-DC currents can cause half-cycle saturation in transformers, leading to harmonic distortion, voltage instability, overheating, and in some instances, total failure (IEEE, 2015; Røen, 2016). The susceptibility of a transformer to GIC is dependent on its construction, such as the winding layout and the geometry of the core (Girgis et al., 2002).

There are multiple instances of transformer damage arising from GIC. The most significant event as of writing was the March 1989 solar storm, where a large solar storm in the Northern Hemisphere caused a total blackout of the Hydro Quebec power grid lasting at least 9 hours in duration (Béland & Small, 2005). The effects of this storm were also seen in the United Kingdom, where two power transformers were damaged as a result of the solar storm (Erinmez et al., 2002). In New Zealand, a solar storm impacted the South Island in November 2001, causing a static VAR compensator to trip at Islington substation. Following the tripping of the SVC, a voltage collapse occurred, causing a power transformer supplying Dunedin city to fail within one minute. Upon inspection of the transformer, it was found that internal flashover was the root cause of the failure, and the transformer was beyond repair, incurring around NZD 2 million worth of damage (Béland & Small, 2005; Marshall et al., 2012). In a United Nations report severe space weather events were identified as a major threat to critical infrastructure and the global economy with the largest potential impacts arising from GIC in electrical power networks. It was highlighted that this could lead to infrastructure damage, loss of services reliant on electricity and in the extreme cases loss of life (United Nations, 2017). Oughton et al. (2017) assessed the potential economic impact an extreme space weather event could have and found that the United States could lose between USD 6.2 to 42 billion in GDP daily with 8% to 66% of the population being without power. It is apparent from these examples that the risk that space weather poses to the grid is not to be taken lightly.

Dissolved Gas Analysis (DGA) is a non-intrusive method of monitoring a transformer's condition that is widely used by asset owners to monitor transformer health. The techniques outlined by IEEE (2008) and the IEC (1999) consist of analysing various gases to determine the transformer condition where the composition of gases can be used to determine the fault type. This analysis is based on the fact that as heating occurs in a transformer, its insulation starts to break down and release combustible gases. Low energy thermal faults involving oil decomposition typically involve significant amounts of Ethylene being released and small quantities of Hydrogen and Ethane. Thermal faults involving cellulose typically involve large amounts of Carbon Monoxide and Carbon Dioxide. High energy faults involving partial discharge are associated with large amounts of Hydrogen and Methane with small quantities of Ethane and Ethylene. Arcing faults generally involve large amounts of Hydrogen and Acetylene with minor amounts of Methane and Ethylene.

Various empirical methods have been developed to determine the fault type in a transformer, including Duval’s Triangle (Duval, 2008) and the Key Gas Ratio (IEEE, 2008). The Low Energy Degradation Triangle (LEDT), developed by Moodley & Gaunt (2012), proposed a method that analysed key gases associated with low energy faults, namely Hydrogen, Methane and Carbon Monoxide. The composition of these gases is combined into a triangular representation to represent the transformer condition. This method is particularly suited to analysing low-energy faults and can indicate the onset of transformer degradation as opposed to Duval’s Triangle, which is useful for determining the cause of existing faults. The LEDT method is well suited for analysing the impact of GICs and has been used in previous studies by Gaunt and Coetzee et al. (2007) and Lewis et al. (2022).

DGA can be used to detect the onset of a fault or diagnose a fault that has already occurred and, as such, has been reported to be useful for monitoring the effects of space weather on large power grid transformers. Gaunt & Coetzee (2007) investigated power transformers in South Africa using DGA alongside practical measurements of GIC and found that GIC may be a significant cause of transformer failures. During the November 2003 solar storm, DGA records from a sample of twelve different South African power transformers showed a sharp change at the onset of the storm, with two of the transformers having gas ratios that were consistent with low-temperature thermal degradation. Following the solar storm, a transformer at Lethabo power station tripped on the 17 November followed by a transformer at Matimba power station tripping on 23 November following a severe storm on 20 November. In June 2004 three more of the transformers in the study had to be taken out of service with high levels of DGA. Upon inspection of the failed transformers damage to the paper insulation was observed which was consistent with the DGA diagnosis.

In contrast, Lewis et al. (2022) assessed the impacts of geomagnetic storms on 13 power station transformers in the United Kingdom using the Low Energy Degradation Triangle method along with a Superposed Epoch Analysis over multiple storm events from 2010 to 2015. The LEDT analysis found that out of the 98 storms analysed 63% of the LEDTs showed operation outside of the normal region. However, the deviation away from the normal region did not appear to be linked to GIC. Superposed Epoch Analysis found that no upwards trend existed in the gas levels of the transformers studied following the onset of each solar storm in that study. Analysis of the gas dataset as a whole found no indication that increasing gas production rates correspond to higher levels of geomagnetic activity. The results of this analysis found no evidence of space weather impacts on the transformers studied. The author noted that these results were likely due to the relatively quiet period of the sun during the analysis period and the modernity of the transformers studied, but might also be impacted by the lack of GIC data, such that it was unclear if the transformers investigated might have high or low GIC levels. The author notes that the South African studies were conducted across multiple case studies during geomagnetically active conditions whereas the British studies were conducted using statistical methods during an extended period of quiet/moderate activity.

While many studies exist on the impacts of GIC on power transformers in New Zealand (Mac Manus et al., 2022; Mukhtar et al., 2020; Rodger et al., 2020), few studies exist that employ DGA techniques to relate GIC magnitudes to transformer gassing. In the current study we attempt to address this research gap by examining DGA data from various power transformers in New Zealand. The study begins by looking at case studies of storms within the sampling period where the individual gases are analysed along with the Low Energy Degradation Triangle in order to establish if geomagnetic activity relates to transformer gassing. Gas concentration levels and magnetic field readings are then analysed over the study's entire sampling period to establish a correlation between geomagnetic activity (dH/dt) and gassing rates.

2 Data and Methods

2.1 Gas Data

New Zealand's power network is owned and operated by Transpower New Zealand Limited. They have provided us with dissolved gas data for eight different transformers across New Zealand located in both the North and South Islands, as outlined in Table 1. The transformer configurations are either three-phase three-limb (3P3L) or single-phase three-limb (1P3L). Transformers with a closed flux path around the core are known to be more susceptible to GIC so we expect the 1P3L transformers to be more vulnerable to GIC induced damage than the 3P3L (Røen, 2016). For the 3P3L units the tank contains all three windings and the oil is sampled from the upper valve, therefore the oil samples are common to all three phases. Note that some transformers have gas data that extends to 2022 however the analysis period only extends to 2019 due to the availability of magnetic field data.

Figure 1 shows the approximate locations of the transformers studied. The analysis period ranges from 2016 to 2019; however, some transformers have shorter analysis periods due to maintenance or decommissioning of the monitoring equipment. Key gases are recorded for each transformer, including Hydrogen (H_2), Carbon Monoxide (CO), Acetylene (C_2H_2), Ethylene (C_2H_4) and Ethane (C_2H_6), which are sampled every four hours. Transpower use a range of DGA monitoring devices from different manufacturers to achieve this measurement. Due to digital sampling, there is quantisation noise present in the data. In order to reduce the effect of this quantisation noise the moving average of the gas data were taken with a window size of 30 samples (5 days) for each transformer. Shorter window lengths were tried but they were found to be insufficient to remove the quantisation noise. This large window size should not affect the outcome of the data analysis as dissolved gas analysis looks at long-term trends in gas levels. It is also worth noting that large fluctuations in the gas data will still be captured in the moving average.

Figure 2 shows the gas data for Roxburgh. As can be seen in Figure 2 the gas data for Roxburgh show an upwards trend in combustible gases with the greatest increase being observed in Carbon Monoxide, which is likely a natural by-product of insulation paper breakdown. Note that transformers normally produce gases as part of natural ageing so not all gas profiles are indicative of a fault (IEEE, 2008).

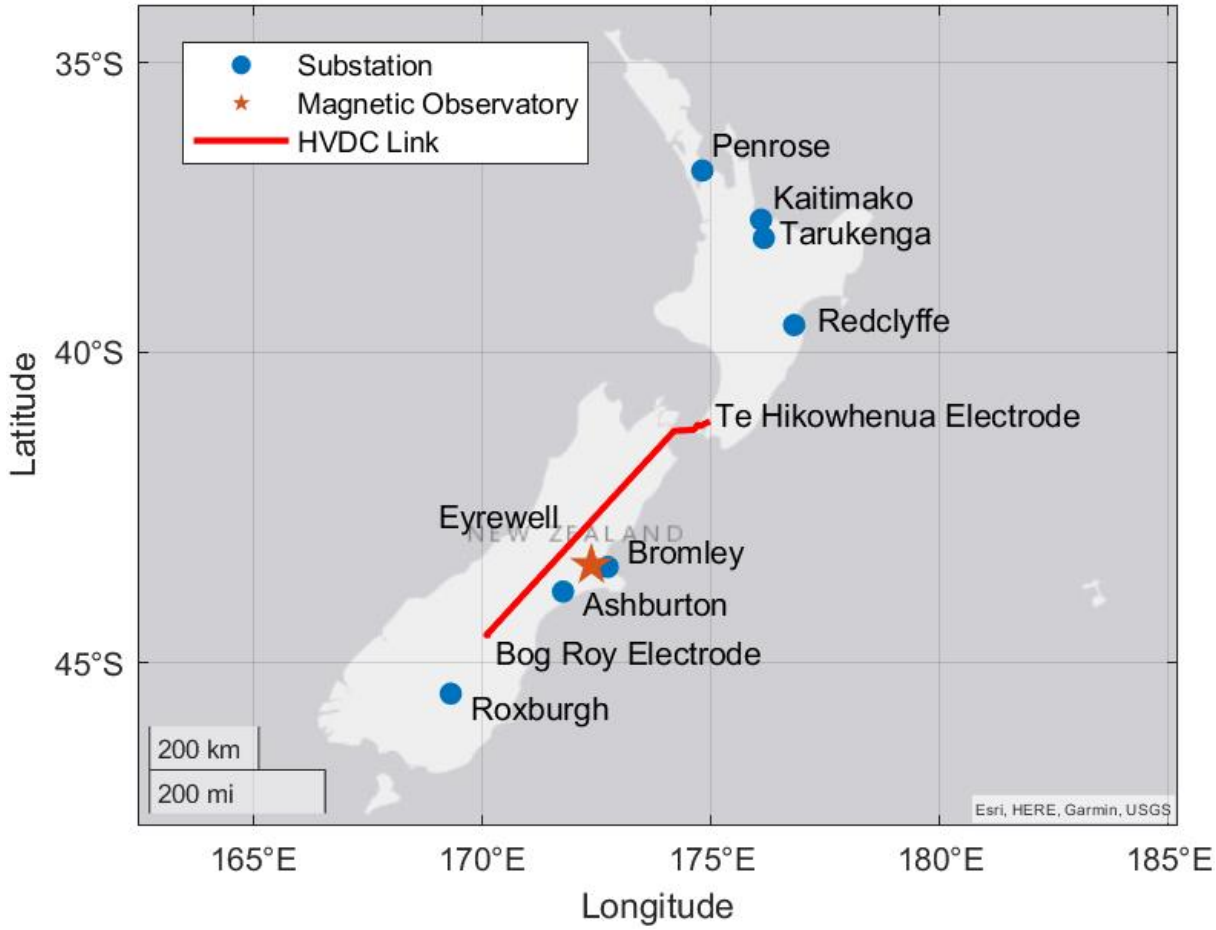


Figure 1. Approximate locations of the substations where DGA records were taken are indicated by the circles. The path of the High Voltage DC Link is indicated by the red solid line and the location of the magnetic observatory is indicated by the star.

Table 1

Summary of the transformers studied, their configuration and the date range for their dissolved gas records.

Transformer	Configuration	Date Range
Bromley	3P3L	January 2016 – January 2022
Roxburgh	3P3L	August 2018 – February 2022
Ashburton	3P3L	January 2016 – July 2018
Tarukenga	1P3L	October 2016 – June 2018
Tarukenga 2	1P3L	January 2016 – September 2018
Penrose	3P3L	January 2016 – December 2017
Kaitimako	3P3L	January 2016 – August 2019
Redclyffe	3P3L	January 2016 – August 2019

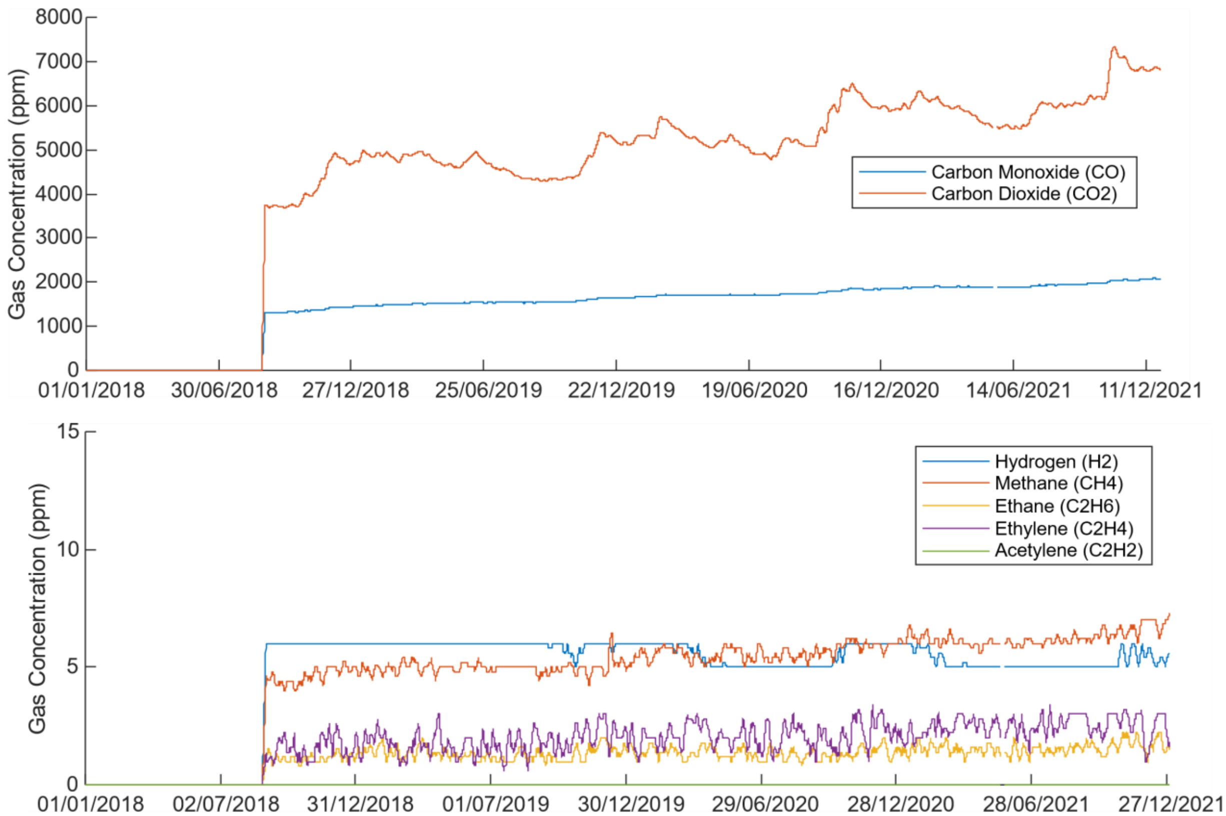


Figure 2. Dissolved gas concentrations from 2018 to 2021 for Roxburgh. Time axis is in coordinated universal time and the date format is in DD/MM/YYYY.

As can be seen by the circles in Figure 1 five of the transformers studied are located in the North Island and three in the South Island. To date the majority of space weather studies have been focused on the lower and mid-South Island as it has been presumed to be at a higher risk of GIC due to its closer proximity to the auroral zone than the North Island (Mukhtar et al., 2020), but also because the majority of GIC observations in New Zealand are located in the South Island. However, recent work has investigated the occurrence of even order Total Harmonic Distortion in New Zealand during geomagnetic disturbances (Rodger et al., 2020). Even harmonic distortion is produced by half cycle saturation due to DC currents such as GIC, and hence can provide evidence of GIC stressing transformers when no GIC measurements are available. The study of Rodger and co-workers examine harmonic distortion for two geomagnetic disturbances across both islands and found enhancements in both.

2.3 Magnetic Data

Magnetic field measurements for this study are taken at the Eyrewell magnetic observatory from 2016 to 2019. The star in Figure 1 shows the location of the observatory. This monitoring site was chosen as it has been used in previous space weather studies (Mac Manus et al., 2022). The observations include absolute measurements of the X, Y and Z components of the Earth's magnetic field. These are sampled using declination-inclination fluxgate magnetometers and a proton precession magnetometer at one-minute intervals at a resolution of 0.1 nT. Of interest to the study is the rate of change in the horizontal component (dH/dt), where the magnitude of *H* is calculated as follows.

$$|H| = \sqrt{X^2 + Y^2} \#(1)$$

where X is the magnetic field aligned positive to geographic north and Y is the magnetic field aligned positive to geographic east. dH/dt is calculated by taking the difference between consecutive measurements. Note that the method in Equation 1 used the magnitude of the magnetic field components rather than the gradient as the field direction does not change much with time, furthermore this method has been used in studies using the same dataset by Mac Manus et al. (2017) and Rodger et al. (2017). Figure 3 shows the rate of change of the magnetic field measurements over the entire sampling period. As can be seen in the graph, the magnetic field at Eyrewell in the time period we consider in our study is relatively quiet, with around two significant disturbances of over 30nT/min in magnitude and several smaller perturbations. In contrast, Rodger et al. (2017) examined peak GIC for 25 larger geomagnetic disturbances with thresholds >40 nT/min.

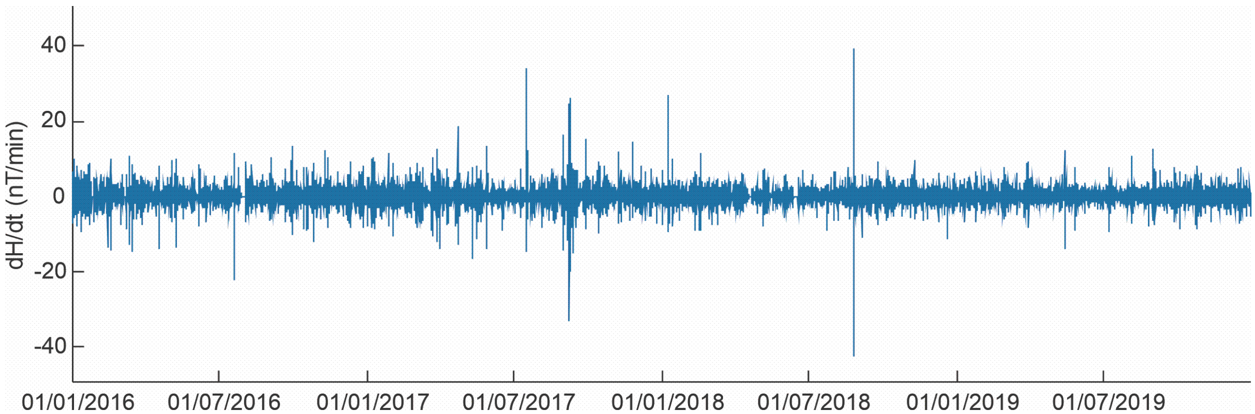


Figure 3. Magnetic field observations from 2016 to 2019 as measured at the Eyrewell magnetic observatory at one-minute time resolution. Time axis is in Coordinated Universal Time.

For the purposes of the study, six geomagnetic disturbance events identified by Mac Manus et al. (2022) were selected to be analysed and presented in Table 2. These events are classified into two large events and four small disturbance events. The small disturbance events were identified to produce a maximum GIC of < 15A but > 1A for at least one transformer in the New Zealand power network. To give an overview of the long duration GIC the five and ten-minute mean GIC is provided.

Table 2
Geomagnetic disturbance events identified by Mac Manus et al. used in the study.

Date	Max dH/dt (nT/min)	Max GIC (A)	5 Minute Mean GIC (A)	10 Minute Mean GIC (A)	Local Time of Maximum GIC	Classification
14 October 2016	8.8	6.9	6.4	5.9	01:51	Small
22 April 2017	18.7	13.5	7.5	5.4	21:30	Small
08 September 2017	33.3	48.9	35.9	26.6	00:42	Large
01 June 2018	5.4	6.7	4.8	3.8	22:05	Small
26 August 2018	43.2	48.2	31.7	22.5	20:04	Large
02 February 2019	3.8	3.4	2.7	2.1	22:15	Small

2.4 Low Energy Degradation Triangle

For determining the transformers condition the Low Energy Degradation Triangle (LEDT) was used. This method was developed by Moodley and Gaunt (2012) and has been used by Lewis et al. (2022) for detecting incipient transformer faults. This triangle uses three dissolved gases as the basis of condition assessment including hydrogen (H_2), methane (CH_4) and carbon monoxide (CO). In order to determine the transformers condition, the composition of these three gases are plotted on a ternary plot, where the concentration of carbon monoxide (%CO) is on the bottom axis, methane (%CH_4) is on the left-hand axis, and hydrogen (%H_2) is on the right-hand axis. The combined concentration of these gases are represented by a point on the plot that moves clockwise with increasing fault energy. Faults have varying levels of energy associated with them. Low energy faults are typically associated with thermal degradation, partial discharge, and corona. In contrast, high energy faults are associated with arcing. As the fault energy increases the point on the triangle moves clockwise away from the lower left-hand vertex towards the right-hand vertex. The LEDT method indicates four regions of operation based on the position of the point on the triangle namely: The normal operation region, partial discharge and corona region, sparking region, and the high energy arcing region. Normal operation occurs when the combined concentration of hydrogen and methane are 20% or below with carbon monoxide dominating at 80% or above. Measurements occurring in this region indicates that the gas production in the transformer is likely due to paper and oil degradation from transformer losses, i.e. normal transformer aging. In the corona discharge region increasing amounts of hydrogen and methane are released with high levels of carbon monoxide. When the carbon monoxide concentration goes below 60% partial discharge starts to occur with associated high levels of methane and hydrogen. This generally indicates the start of major insulation breakdown. Sparking occurs due to high voltage flashovers at low current resulting in increased levels of methane. The occurrence of sparking is indicated by the apex region of the triangle where the concentration of methane is 80% or above. High energy arcing is associated with high currents and thus high temperatures producing high levels of hydrogen with small quantities of methane. If paper insulation is also involved, there will also be significant amounts of carbon monoxide present. The high energy arcing region is indicated in the right-hand corner of the plot, where the carbon monoxide levels are 20% or below and the combined methane and hydrogen levels are 50% or below.

It is of worth to note that the LEDT method is relatively new as of writing and has not been adopted into international standards (IEC, 1999; IEEE, 2008). Well established methods like Duval’s Triangle specify minimum gas levels for the diagnosis to be valid (Duval, 2008). Since the LEDT is used for diagnosing low energy faults it could be valid for low gas concentrations however this has not been established in the literature. Most of the transformers being studied have relatively low gas concentrations throughout the observation period and thus Duval’s Triangle would not be effective at detecting incipient faults. We believe that the LEDT method is an effective method for detecting GIC related faults as they develop and has been used in previous studies by Gaunt et al. (2017) and Lewis et al. (2022).

For our study an LEDT was plotted for each of the eight transformers during their respective gas sampling periods. The points on the triangle were then compared to the magnetic field data to discern whether faulting has occurred after a geomagnetic storm, and also how the fault has evolved with time.

2.5 Case Studies

Multiple case studies were conducted during the large and small geomagnetic events listed in Table 2. For each case study, the individual gases in each transformer were analysed seven days before and after the storm's onset. From this analysis, it can be established whether the production of combustible gasses corresponds to an increase in geomagnetic activity. This case study comparison is detailed more 3.1-3.3, below.

2.6 Correlations

In addition to individual case studies, the dataset as a whole was analysed to establish if there is a correlation between raw gassing rates and geomagnetic activity. In the current study, the mean and maximum change in horizontal component of magnetic field over four hours at Eyrewell (dH/dt) was compared with the hourly rate of change of the six combustible gases. This was analysed for all eight transformers over the entire observation period of the dataset, which spans from 2016 to 2019. The gas rates were derived from the gas dataset by taking the difference between subsequent raw gas readings averaged over a four-hour period and scaling them to obtain the hourly rate of change. A four-hour period for obtaining the mean and maximum magnetic field readings was chosen to match the sampling rate of the gas readings. We discuss the results of this analysis in section 3.4. Note that the gas data were not averaged for this analysis, instead the raw data was used.

3 Results

3.1 September 2017 Large Storm

Figure 4 presents a case study during the September 2017 Geomagnetic Storm. This geomagnetic disturbance has been described in detail by Clilverd et al. (2018). Harmonic distortion was observed across New Zealand during this event (Rodger et al., 2020), and GIC was seen globally (Clilverd et al., 2021; Dimmock et al., 2019; Piersanti et al., 2019). During the peak of the storm, the maximum change in horizontal component measured at Eyrewell was 33.3 nT/min, with a maximum GIC of 48.9A being measured. As seen in Figure 4, the gas concentrations stay approximately constant during the entire observation period in the transformer at Tarukenga with the variation in Ethylene and Acetylene likely due to quantisation noise. The same trend was observed for the other transformers in the study. Note that the transformer at Roxburgh was excluded from this case study as gas data does not exist for this transformer during this storm period.

Figure 5 shows the Low Energy Degradation Triangles for the transformers at Tarukenga (in this case Tarukenga transformer number 2) and Ashburton during the September 2017 storm; it can be seen that during this period, the points on the triangles show no movement and are within the normal operation region as the point on the triangle is in the lower left-hand corner indicating that a fault has not occurred during this period. Similar trends were observed for the remaining transformers.

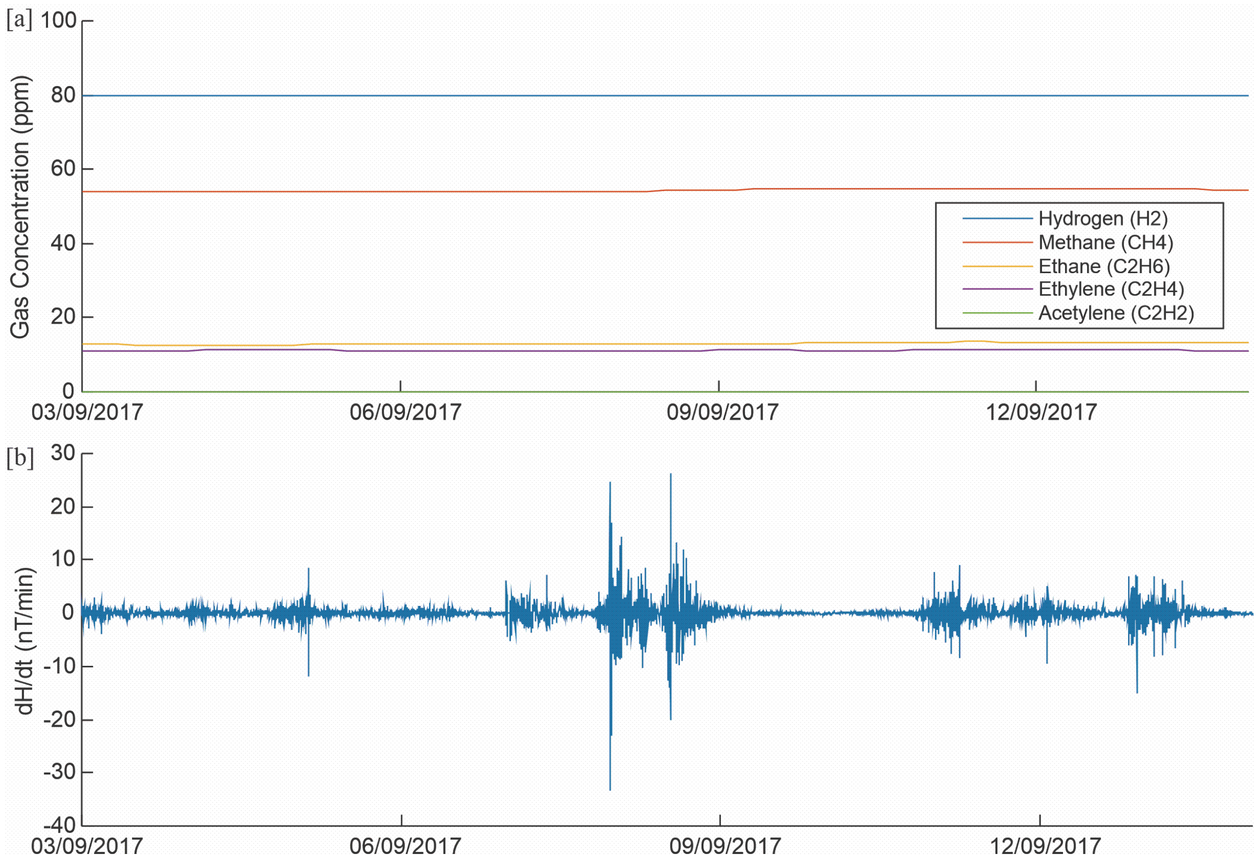


Figure 4. Dissolved gas concentrations at Tarukenga 2 [a] and change in the horizontal magnetic component at Eyrewell [b] for the September 2017 geomagnetic storm.

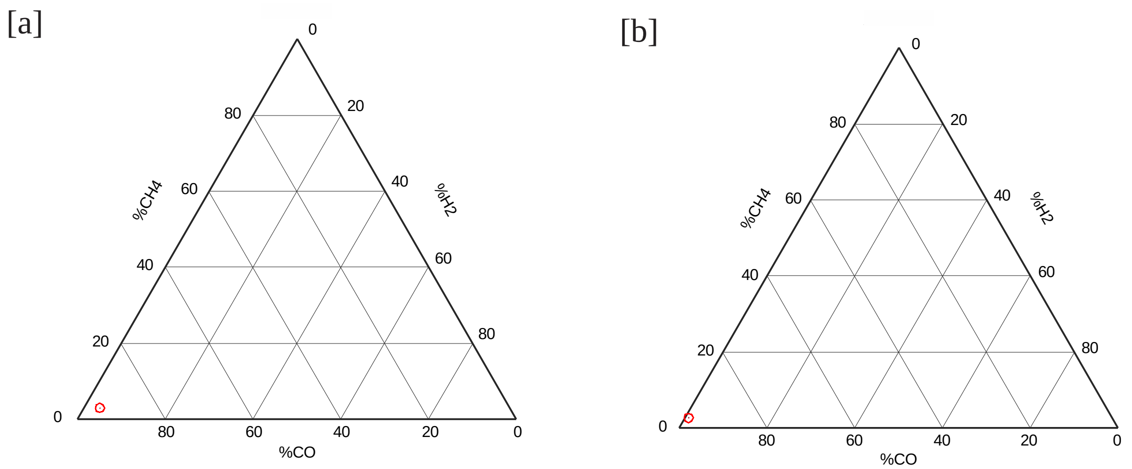


Figure 5. Low Energy Degradation Triangle for transformers at Tarukenga 2 [a] and Ashburton [b] during the September 2017 geomagnetic storm.

3.2 August 2018 Large Storm

Figure 6 shows the dissolved gas concentration and GIC at the transformer in Bromley, along with the change in the horizontal magnetic component at Eyrewell. It can be seen that the gas concentration and GIC are approximately constant with only minor perturbations over the observation period that were most likely due to noise. This indicates that the geomagnetic storm is likely not associated with transformer gassing. Similar trends were observed for the other transformers during this time period.

Figure 7 depicts the Low Energy Degradation Triangle for the transformers at Bromley and Redclyffe, for this storm. Bromley shows signs of a high energy fault involving temperatures in excess of 300°C. High concentrations of Carbon Monoxide and Hydrogen indicate that the fault may involve partial discharges in Cellulose. The LEDT for Redclyffe indicates the beginning of a low-temperature thermal fault in excess of 110°C. Analysis of the gas readings for Redclyffe during the storm period found that there was an increasing trend of Hydrogen, Methane, Ethane, and Carbon dioxide, indicating that the supposed faulting may involve the decomposition of oil. There is no indication, however, that these diagnoses are due to geomagnetic activity as there was no significant fluctuations in combustible gas levels observed during or after the geomagnetic storm and hence no movement in the LEDT triangles. Also since the gas levels observed in the Bromley and Redclyffe transformers are very low compared to typical values the diagnoses are not of concern to Transpower.

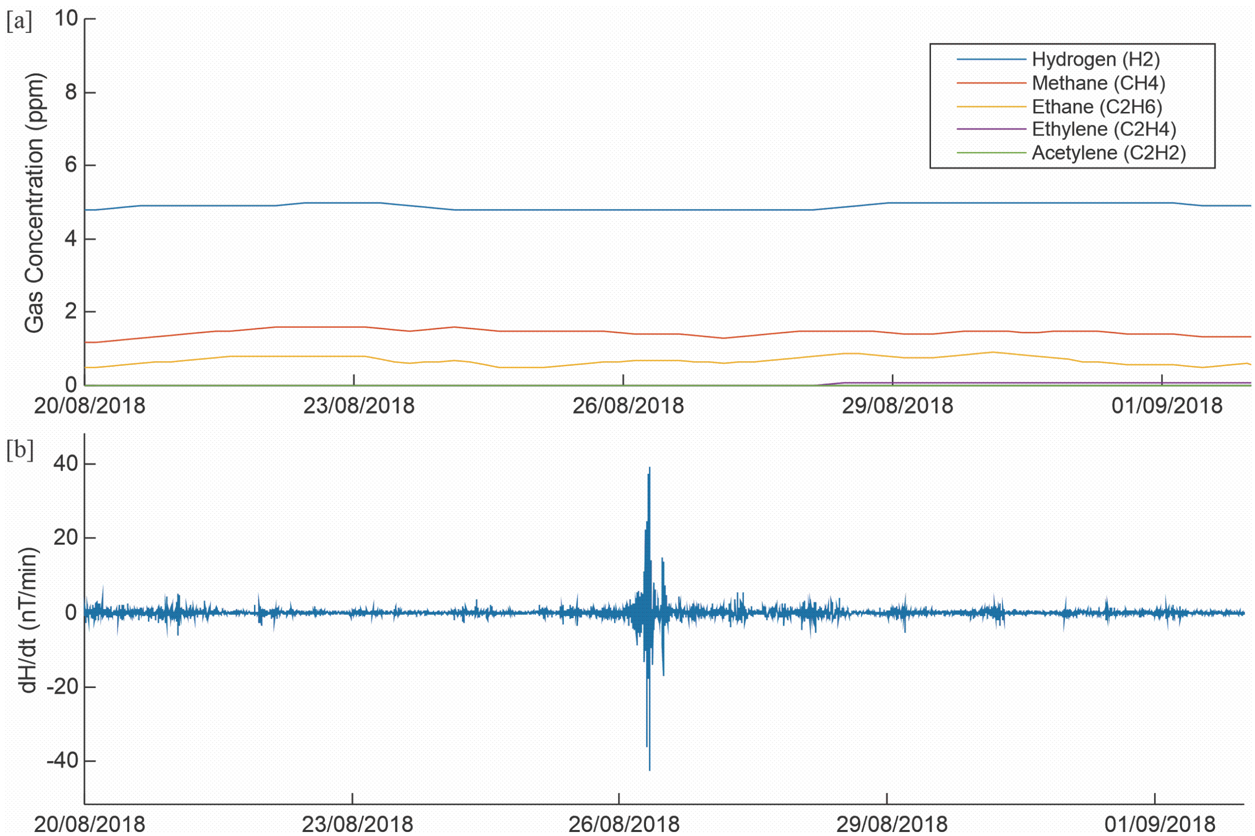


Figure 6. Dissolved gas concentrations at Bromley [a] and change in the horizontal magnetic component at Eyrewell [b] for the August 2018 geomagnetic storm. Time axis is in Coordinated Universal Time.

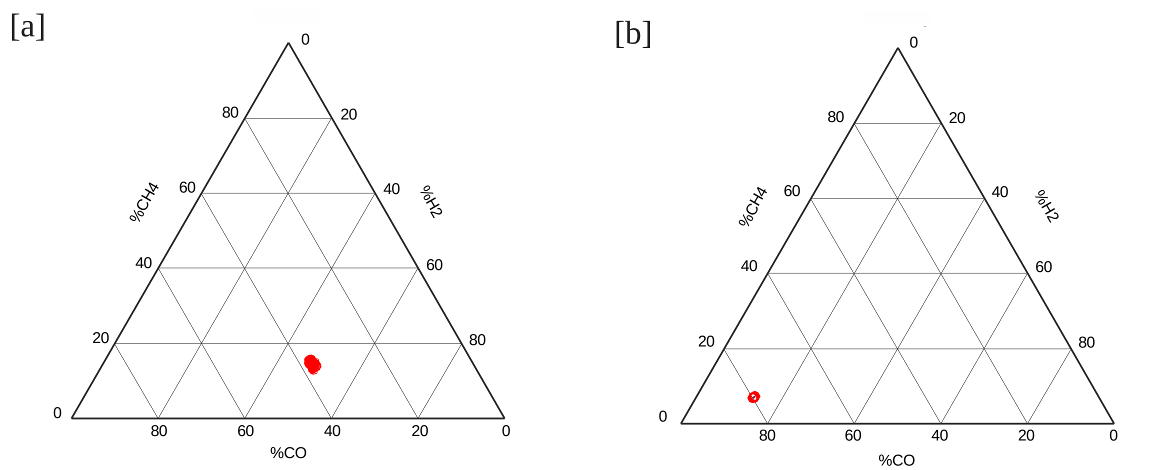


Figure 7. Low Energy Degradation Triangle for transformers at Bromley [a] and Redclyffe [b] during the August 2018 geomagnetic storm.

3.3 Four Small Storms

Analysis of the four smaller storms found no correlation between increases in geomagnetic activity and the production of combustible gasses for all of the transformers studied. Figure 8 shows the gas concentrations for the transformer at Roxburgh during the February 2019 storm and no significant fluctuations were observed in the gas readings. Similar trends were observed for the remaining transformers for all of the smaller storms studied, and hence they are not presented.

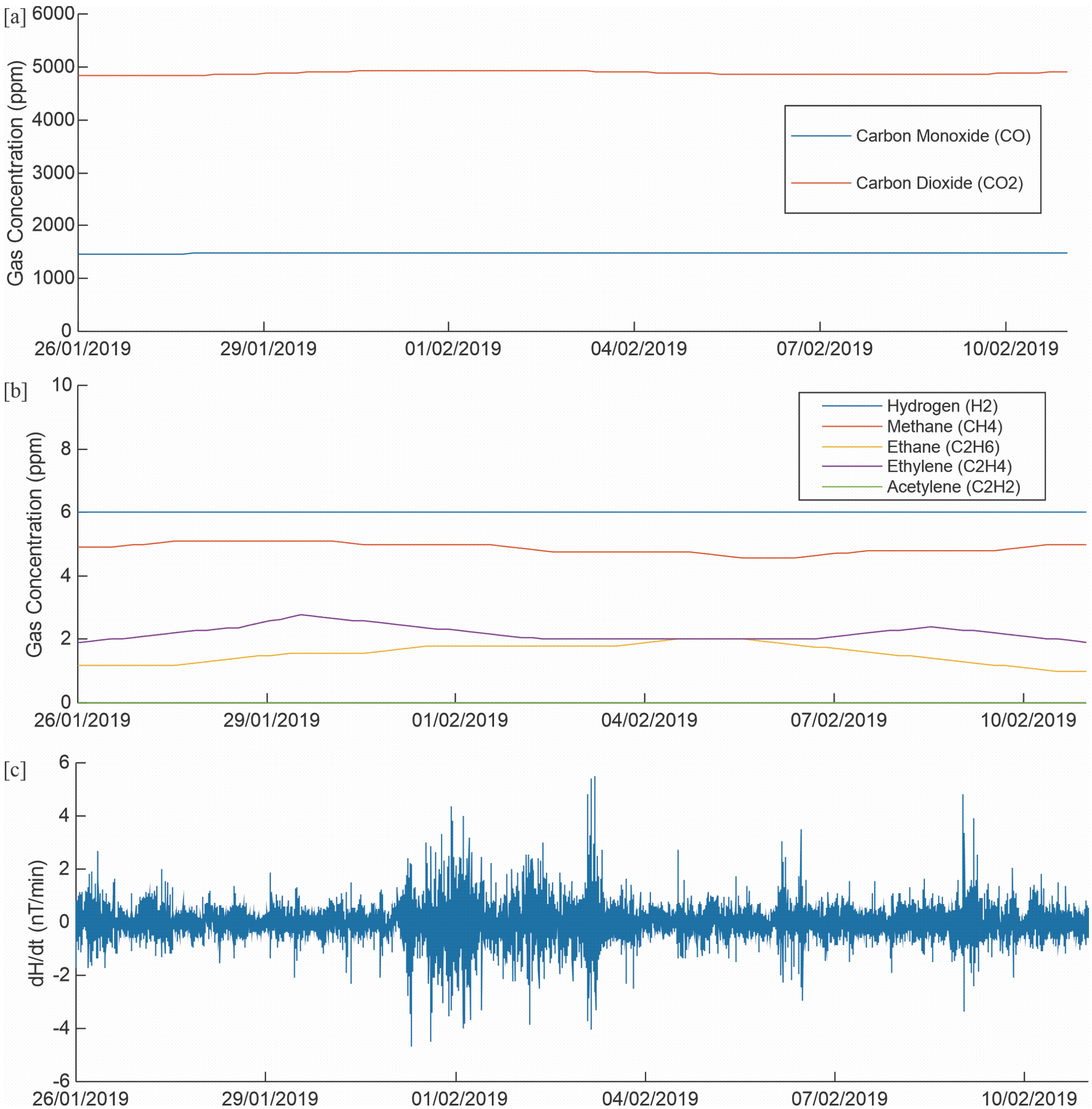


Figure 8. Dissolved gas concentrations at Roxburgh [a] and [b] and the change in the horizontal magnetic component at Eyrewell [c] for the February 2019 geomagnetic storm. Time axis is in Coordinated Universal Time.

3.4 Correlations

3.4.1 Geomagnetic Disturbances

In order to establish if there is a link between gas production and magnetic disturbances for the entire observation period, individual gas rates for all of the transformers studied were compared against the change in the horizontal magnetic field component with four-hour time resolution starting at 12:00 UTC at Eyrewell (dH/dt). Figure 9 shows the combustible gas rates (in ppm/hr) against the maximum change in the horizontal magnetic field over four hours on a logarithmic scale. As seen in the graphs, most of the data points lie where the gas production rates equal zero. Where the gas production rates are non-zero, most of the data points are spread symmetrically about the y-axis or are located at the origin, indicating that a majority of the gassing associated with geomagnetic disturbances is due to noise in the dissolved gas measurements.

Figure 10 shows the combustible gas rates against the mean change in the horizontal magnetic field over a four-hour period on a logarithmic scale. A similar trend, as seen in Figure 9, can be observed where a majority of the non-zero gas readings can be attributed to noise. From this analysis, it is apparent that geomagnetic disturbances show little correlation with gas production rates for the observation period.

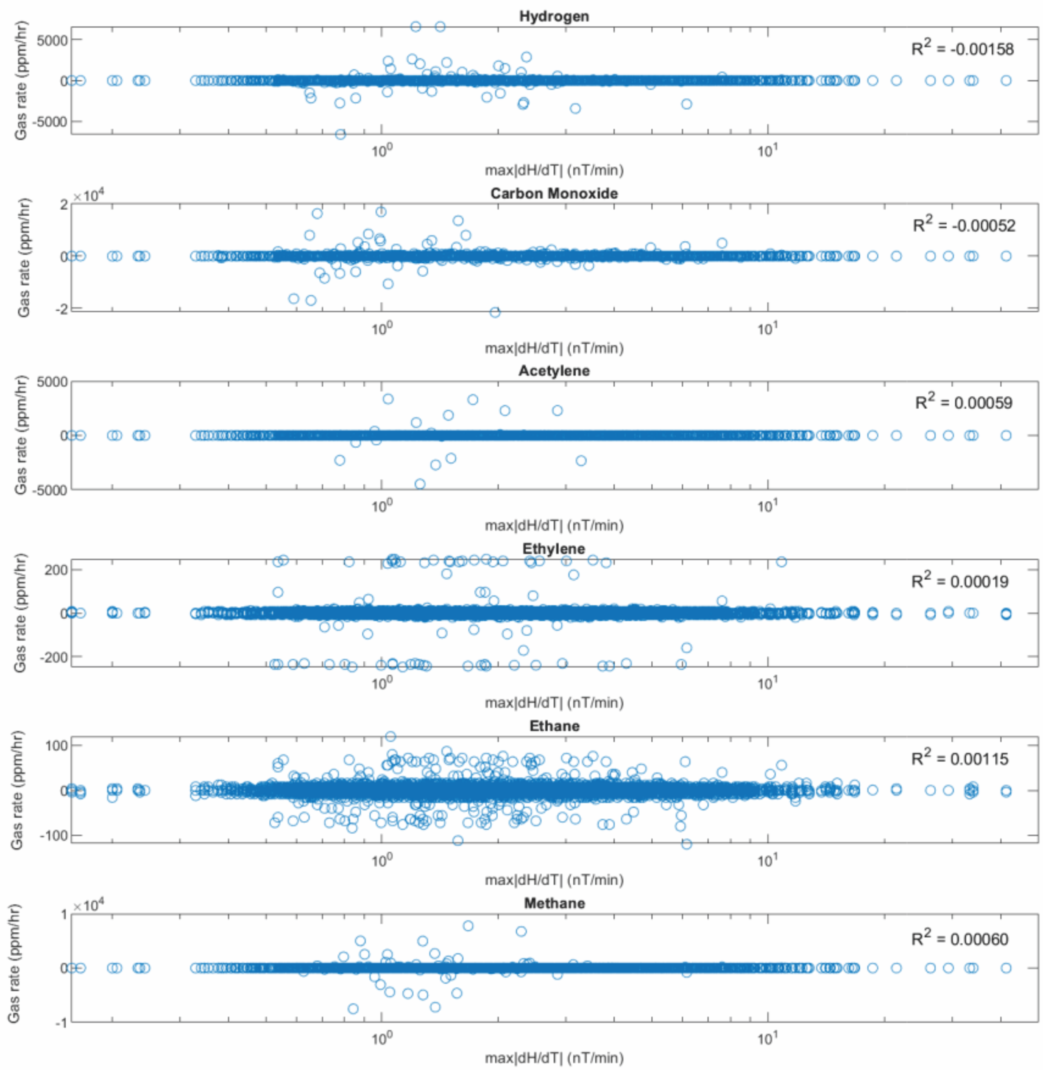


Figure 9. Plot showing the relationship between the maximum change in horizontal component at Eyrewell

(max|dH/dT|) and combustible gas rates for all the transformers studied from 2016 to 2019.

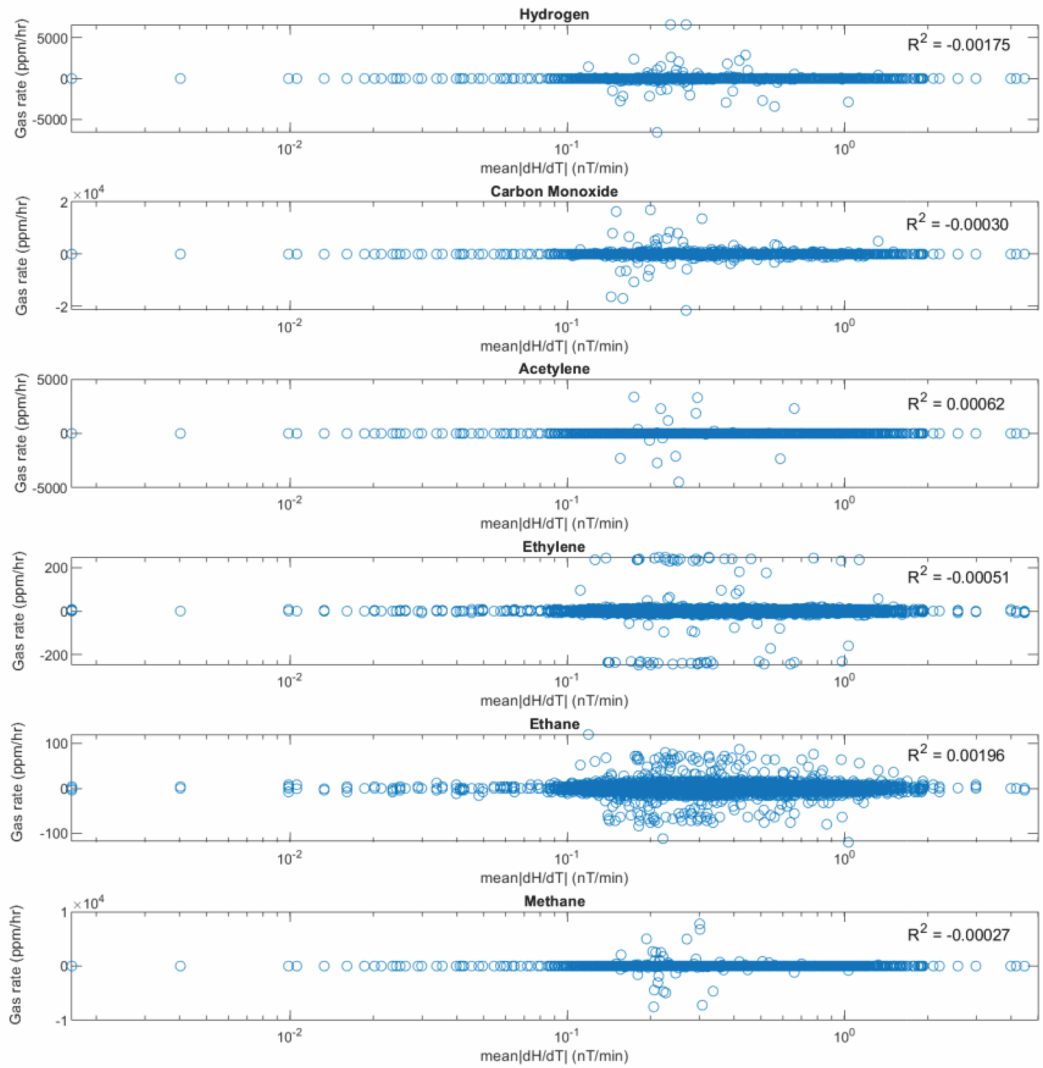


Figure 10. Plot showing the relationship between the mean change in horizontal component at Eyrewell (mean|dH/dT|) and combustible gas rates for all the transformers studied from 2016 to 2019.

4 Discussion and Conclusions

This study analysed DGA measurements made across eight transformers in the New Zealand transformer network and compared them with magnetic field observations occurring during the time period from 2016 to 2019. The purpose was to establish if there was a link between the production of combustible gasses in a transformer and geomagnetic activity. Case studies were performed analysing dissolved gas measurements along with magnetic field observations for two large and four smaller storms. From all of these studies, no link was found between transformer gassing and geomagnetic activity for all the transformers studied.

Analysis of the LEDTs of the transformers during these periods found that a majority of the transformers were operating within their normal region, with three transformers operating outside of the normal region at some point in the study. This deviation away from the normal region is unlikely to be caused by geomagnetic activity and was not of concern to Transpower. The author notes that the LEDT is not included in any standards for transformer condition monitoring and, therefore cannot be relied upon to make a formal diagnosis. Also, standardized methods that use gas ratios require the absolute levels of transformer gases to be above certain levels (Typical Gas Concentration, TGC) to be a valid diagnosis. The levels of gas in the transformers studied is considered to be low for standard ratio analysis.

In order to establish if the production of gasses correlates with geomagnetic activity, the individual gas rates for the entire sample of eight transformers being studied are compared with the maximum and mean change in the magnetic field at Eyrewell for the entire observation period. This analysis showed no correlation between an increase in combustible gas concentration and geomagnetic activity.

It is worth noting that the gas data being studied does not span the entire observation period for all the transformers. Furthermore, the transformers in the study were identified by Transpower to be producing abnormal concentrations of gas and, as such, could have been developing a fault well before the observation period.

It is important to note that this study was limited by the availability of suitable data. The geomagnetic disturbances during the time period studied were small compared to previous events with the highest disturbance being recorded to have a magnitude of only around 40nT/min. Storms which are known to have caused damage to transformers in New Zealand have been recorded to have peak magnetic disturbances of up to 190nT/min (Rodger et al., 2017). The availability of DGA data has also limited the findings of the study as the transformers known to have experienced high amounts of GIC during geomagnetic disturbances have no DGA measurements.

What is also worth mentioning is that the majority of the transformers studied in this paper were located on the North Island, with only three of the transformers being located in the South Island. The South Island is identified to have a higher susceptibility to GIC than the North due to its closer proximity to the poles (Mukhtar et al., 2020). Therefore, an area of further research would be to observe transformer gassing for more transformers in the South Island. Furthermore, the South Island also has a large range of GIC observations that could be utilised, which might provide additional insight.

The implications of this research is that the production of combustible gasses in a power transformer is unlikely correlated to geomagnetic storms for the time period analysed. This echoes the findings by Lewis et al. (2022) which analysed power transformers in the United Kingdom and found similar results. Analysis of DGA data during more geomagnetically active periods in which transformer damage is known to have occurred may yield different results.

Another area of research would be to expand this study to analyse periods of greater solar activity, as the magnetic field measurements made at Eyrewell were relatively quiet from 2016 to 2019 and suitable DGA data was not available outside of this time period. These periods of interest could include the November 2001 storm (Rodger et al., 2017), which was known to have caused damage to transformers in New Zealand.

Acknowledgments

This research was supported by the New Zealand Ministry of Business, Innovation and Employment Endeavour Fund Research Programme contract UOOX2002. The author would like to thank Transpower New Zealand for providing the dissolved gas analysis data for the New Zealand power transformers. Magnetic field data was collected at Eyrewell. We thank GNS, for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org).

Open Research

The magnetometer data used for the data analysis in the study is available at (INTERMAGNET et al., 2021) under a Creative Commons Attribution Non-Commercial 4.0 International License. The DGA data was provided to us by Transpower New Zealand with caveats and restrictions. This includes requirements of permission before all publications and presentations. In addition, we are unable to directly provide the DGA data. Requests for access to the measurements need to be made to Transpower New Zealand. At this time the contact point is Jon Brown (Jon.Brown@transpower.co.nz). We are very grateful for the substantial data access they have provided, noting that this can be a challenge in the Space Weather field (Hapgood & Knipp, 2016).

References

Béland, J., & Small, K. (2005). Space Weather Effects on Power Transmission Systems: The Cases of Hydro-Québec and Transpower New ZealandLtd. In I. A. Daglis (Ed.), *Effects of Space Weather on Technology Infrastructure* (pp. 287–299). Dordrecht: Springer Netherlands. doi: 10.1007/1-4020-2754-0_15

Clilverd, M. A., Rodger, C. J., Brundell, J. B., Dalzell, M., Martin, I., Mac Manus, D. H., … Obana, Y. (2018). Long-Lasting Geomagnetically Induced Currents and Harmonic Distortion Observed in New Zealand During the 7–8 September 2017 Disturbed Period. *Space Weather*, *16*(6), 704–717. doi: 10.1029/2018SW001822

Clilverd, M. A., Rodger, C. J., Freeman, M. P., Brundell, J. B., Manus, D. H. M., Dalzell, M., … Frame, I. (2021). Geomagnetically induced currents during the 07–08 September 2017 disturbed period: A global perspective. *Journal of Space Weather and Space Climate*, *11*, 33. doi: 10.1051/swsc/2021014

Dimmock, A. P., Rosenqvist, L., Hall, J.-O., Viljanen, A., Yordanova, E., Honkonen, I., … Sjöberg, E. C. (2019). The GIC and Geomagnetic Response Over Fennoscandia to the 7–8 September 2017 Geomagnetic Storm. *Space Weather*, *17*(7), 989–1010. doi: 10.1029/2018SW002132

Duval, M. (2008). The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers. *IEEE Electrical Insulation Magazine*, *24*(6), 22–29. doi: 10.1109/MEI.2008.4665347

Erinmez, I. A., Kappenman, J. G., & Radasky, W. A. (2002). Management of the geomagnetically induced current risks on the national grid company's electric power transmission system. *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*(5), 743–756. doi: 10.1016/S1364-6826(02)00036-6

Gaunt, C. T., & Coetzee, G. (2007). Transformer failures in regions incorrectly considered to have low GIC-risk. *2007 IEEE Lausanne Power Tech*, 807–812. doi: 10.1109/PCT.2007.4538419

Girgis, R., Vedante, K., & Burden, G. (2014). A process for evaluating the degree of susceptibility of a fleet of power transformers to effects of GIC. *2014 IEEE PES T&D Conference and Exposition*, 1–5. doi: 10.1109/TDC.2014.6863193

Hapgood, M., & Knipp, D. J. (2016). Data Citation and Availability: Striking a Balance Between the Ideal and the Practical. *Space Weather*, *14*(11), 919–920. doi: 10.1002/2016SW001553

IEC, I. (1999). *Mineral oil-impregnated electrical equipment in service: Guide to the interpretation of dissolved and free gases analysis*. International Electrotechnical Commission.

IEEE. (2008). IEEE guide for the interpretation of gases generated in oil-immersed transformers. *Standard C57. 104*.

IEEE. (2015). IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances. *IEEE Stand.*, *57*.

INTERMAGNET, Altay-Sayan Branch Of Geophysical Survey Of Siberian Branch Of Russian Academy Of Sciences (Russia), Bureau Central De Magnétisme Terrestre, B. (France), Beijing Ming Tombs Geomagnetic Observatory Center, I. O. G. A. G., Bogaziçi University, K. O. A. E. R. I. (Turkey), British Antarctic Survey (United Kingdom), … Saint Petersburg Branch Of Pushkov Institute Of Terrestrial Magnetism, I. A. R. W. P. O. T. R. A. O. S. I. S. B. (Russia). (2021). *Intermagnet Reference Data Set (IRDS) 2018 – Definitive Magnetic Observatory Data* [Data set]. GFZ Data Services. doi: 10.5880/INTERMAGNET.1991.2018

Lewis, Z. M., Wild, J. A., Allcock, M., & Walach, M.-T. (2022). Assessing the Impact of Weak and Moderate Geomagnetic Storms on UK Power Station Transformers. *Space Weather*, *20*(4), e2021SW003021. doi: 10.1029/2021SW003021

Mac Manus, D. H., Rodger, C. J., Ingham, M., Clilverd, M. A., Dalzell, M., Divett, T., … Petersen, T. (2022). Geomagnetically Induced Current Model in New Zealand Across Multiple Disturbances: Validation and Extension to Non-Monitored Transformers. *Space Weather*, *20*(2), e2021SW002955. doi: 10.1029/2021SW002955

Mac Manus, Daniel H., Rodger, C. J., Dalzell, M., Thomson, A. W. P., Clilverd, M. A., Petersen, T., … Divett, T. (2017). Long-term geomagnetically induced current observations in New Zealand: Earth return corrections and geomagnetic field driver. *Space Weather*, *15*(8), 1020–1038. doi: 10.1002/2017SW001635

Marshall, R. A., Dalzell, M., Waters, C. L., Goldthorpe, P., & Smith, E. A. (2012). Geomagnetically induced currents in the New Zealand power network. *Space Weather*, *10*(8). doi: 10.1029/2012SW000806

Molinski, T. S. (2002). Why utilities respect geomagnetically induced currents. *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*(16), 1765–1778. doi: 10.1016/S1364-6826(02)00126-8

Moodley, N., & Gaunt, C. T. (2012). Developing a power transformer low energy degradation assessment triangle. *IEEE Power and Energy Society Conference and Exposition in Africa: Intelligent Grid Integration of Renewable Energy Resources (PowerAfrica)*, 1–6. doi: 10.1109/PowerAfrica.2012.6498647

Moodley, N., & Gaunt, C. T. (2017). Low Energy Degradation Triangle for power transformer health assessment. *IEEE Transactions on Dielectrics and Electrical Insulation*, *24*(1), 639–646. doi: 10.1109/TDEI.2016.006042

Mukhtar, K., Ingham, M., Rodger, C. J., Mac Manus, D. H., Divett, T., Heise, W., … Petersen, T. (2020). Calculation of GIC in the North Island of New Zealand Using MT Data and Thin-Sheet Modeling. *Space Weather*, *18*(11), e2020SW002580. doi: 10.1029/2020SW002580

Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W. P., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, *15*(1), 65–83. doi: 10.1002/2016SW001491

Piersanti, M., Di Matteo, S., Carter, B. A., Currie, J., & D'Angelo, G. (2019). Geoelectric Field Evaluation During the September 2017 Geomagnetic Storm: MA.I.GIC. Model. *Space Weather*, *17*(8), 1241–1256. doi: 10.1029/2019SW002202

Pulkkinen, A. (2003). *Geomagnetic Induction During Highly Disturbed Space Weather Conditions: Studies of Ground Effects*.

Rodger, C. J., Clilverd, M. A., Mac Manus, D. H., Martin, I., Dalzell, M., Brundell, J. B., … Watson, N. R. (2020). Geomagnetically Induced Currents and Harmonic Distortion: Storm-Time Observations From New Zealand. *Space Weather*, *18*(3). doi: 10.1029/2019SW002387

Rodger, C. J., Mac Manus, D. H., Dalzell, M., Thomson, A. W. P., Clarke, E., Petersen, T., … Divett, T. (2017). Long-Term Geomagnetically Induced Current Observations From New Zealand: Peak Current Estimates for Extreme Geomagnetic Storms. *Space Weather*, *15*(11), 1447–1460. doi: 10.1002/2017SW001691

Røen, B. (2016a). Geomagnetic Induced Current Effects on Power Transformers. *109*. Retrieved from https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2407592

United Nations Committee on the Peaceful Uses of Outer Space Expert Group on Space Weather. (2017). (2017). *Report on thematic priority 4: International Framework for Space Weather Services for UNISPACE+ 50 (A/AC. 105/1171)*.