GEOTHERMAL SPRING TEMPERATURE ANALYSIS

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ABSTRACT

The aim of this study was to examine spring temperature time-series data recorded from two geothermal pools, the Waiotapu Geyser in Waiotapu and the Soda Fountain in Orakei Korako. Both springs show cyclic behaviour in their temperature recordings. The Waiotapu Geyser shows a distinct cyclic pattern throughout some periods followed by periods of constant temperature (around 80 °C), whereas the Soda Fountain shows persistent cyclic patterns at all times.

The effects of seismic activity, rainfall, air temperature and air pressure were analysed in order to ascertain whether there are any relationships between the spring temperatures and any of these factors. Seismic events, air temperature and rainfall did not appear to have much impact on the Waiotapu Geyser throughout the period analysed. However, it was found that variations in air pressure could set off or inhibit eruptions at the Waiotapu Geyser as well as affecting its eruption frequency. Generally, during periods of high air pressure the geyser did not erupt and its temperature was constant. However, as the air pressure dropped, the geyser began to erupt; further lowering of the air pressure had the effect of making eruptions more frequent.

The Soda Fountain on the other hand did not seem to be affected by seismic activity, rainfall, air pressure, or air temperature throughout the period analysed. This spring did however show a persistent one- to two-hourly temperature cycle.

Recommendations for future monitoring, based on lessons learnt from this data analysis are: ensuring continuous data collection rather than discrete datasets; co-recording of water level or pressure data; and taking multi-level temperature measurements in the spring feed channel.

1. INTRODUCTION

New Zealand's regional councils monitor selected geothermal springs to fulfil their legislative responsibility for management of New Zealand's geothermal resources. The subject of this study is data collected from geothermal features as part of the Waikato Regional Council Geothermal Feature Monitoring Programme. The data was collected from the Waiotapu Geyser at the Waiotapu Thermal Area, and the Soda Fountain Pool at Orakei Korako. Both Waiotapu and Orakei Korako are located in the Taupo Volcanic Zone (TVZ) of the North Island, New Zealand (Figure 1), and are high-temperature, two-phase, liquid-dominated geothermal systems.

The data presented here is temperature time-series data from two boiling or near-boiling springs. Each time series is 45 days long, and the time between data collection points is two minutes. The two springs which are the subjects of this study exhibit cyclic temperature variation. The pools also exhibit water-level changes, although unfortunately these were not recorded due to equipment limitations.

This study is a qualitative and quantitative analysis of the data from the two springs described above. Avenues of investigation were:

- a relation between climate data (rainfall, air pressure and air temperature) and spring temperature;
- whether there are dominant frequencies in the cyclic data.

Publicly-available climate data from the National Institute of Water and Atmospheric Research Taupo AWS station, and seismic data from the Geonet website have been used to investigate if there is any correlation of this data with spring temperature. However, in this instance the seismic network is too sparse to accurately locate the seismic events and this avenue of investigation has not been pursued.

The first high-temperature spring, the Waiotapu Geyser, has a mean temperature over the recording time of 86.76°C, and shows times of strong cyclic activity that continues for two to six days, with intervening times of non-cyclic behaviour. Data from this spring has a distinctive temperature cycle 'shape' that appears to be independent of frequency. The shape of the cycle indicates the periods of heating, geyser eruption, and cooler water recharge.

The pattern of temperature variation appears to have a close correspondence with air pressure. The relation of air pressure and heating time, refilling time, and eruption frequency are analysed. The possible effect of rainfall is also discussed, although there is not a large enough continuous dataset to conclusively say that rainfall affects spring temperature.

The second spring, the Soda Fountain at Orakei Korako, exhibits cyclic temperature variation over the entire data collection interval. This does not show any correspondence with climatic variables. Inspection of the data shows that there are periods where the water has dropped below the level of the data-logger probe, meaning the data is not suitable for a Fourier analysis, but a Fourier analysis of remaining subsets of data gives the dominant frequencies in each subset.

It is possible that there may be longer-term correspondence between seasonal climate variation and spring activity.

This would be difficult or impossible to identify with the short and intermittent datasets in this study.

In addition to the information obtained from the available data, we suggest improved data collection techniques which would improve our understanding of both spring temperature and water-level variation.

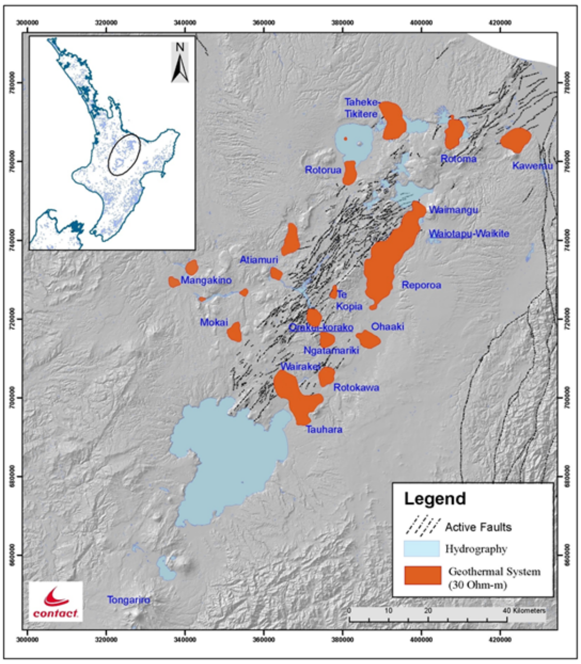

Figure 1. The Taupo Volcanic Zone (insert is the North Island of New Zealand). The geothermal systems are identified by the outline of the ground resistivity at approximately 500 m depth. Waiotapu is part of the greater Waimangu–Reporoa system.

2. THE WAIOTAPU GEYSER

2.1 Temperature Data

The Waiotapu Geyser is a small, intermittently-geysering, mixed chloride-bicarbonate water spring in the Waiotapu Thermal Area. This section describes the features of the spring temperature time series, and also the characteristics of a single temperature cycle. Unfortunately the exact depth of the data logger temperature probe was never recorded, but it was thought to be approximately 0.6 m below the water level of the pool.

The four temperature time-series datasets collected from the Waiotapu Geyser are shown in Figure 2, together with air temperature and air pressure records. All datasets show periods of relatively constant spring temperature, followed by periods of temperature variation showing a distinct and repetitive cycle with an amplitude of ~18 °C.

One prominent feature of the dataset, when in cyclic mode, a distinct and repetitive pattern can be observed. The cycle is sometimes stretched or squeezed but nevertheless retains its basic shape. A typical cycle (see Figure 3) consists of a relatively sharp rise in temperature peaking at about 100°C, dropping suddenly by ~ 20°C before rising sharply to about half its original height; it then gradually decreasing to the original level. The cycle then repeats itself.

We assume that the cyclic behaviour observed in the spring temperature is due to the geyser erupting. The temperature heats up to around 100°C and stays there for about 7–15 minutes which is likely to be the eruption time of the geyser (as the water would be boiling at this stage). After the eruption there is a drop in temperature in which the cold water inflow replaces the lost (hotter) water.

A consistent feature in the cycle is a sudden drop in temperature after an eruption followed by a sharp rise. One possible explanation for this downward spike may be that the water level drops slightly below the point where the data-logger has been inserted after an eruption due to the loss of water. This was also observed by Saptadji (1995) in the temperature curves for a laboratory geyser model. Note that the probe would still be in a steam filled cavity walled in by warm rock, and the temperature might not drop to surface ambient.

When not in this cyclic mode, the temperature is fairly constant and below boiling, which is interpreted here as a quiescent interval.

2.2 The effects of air pressure

Figure 2 shows an apparent relationship between spring temperature and air pressure; periods of higher air pressure generally correspond to periods of inactivity, while periods of low air pressure correspond to periods of cyclic activity in the spring temperature. It also appears that lowering the air pressure seemed to increase the temperature cycle's frequency.

This suggests that air pressure is a possible driving force behind the eruptions and their frequency. There may be several possible explanations as to how air pressure is driving geyser activity. One is that there is a relationship between air pressure and the geyser refilling rate and/or the geyser heating rate as defined in Figure 3**.** To test this idea on the data, we devised an algorithm which finds peaks and lows in the data, stores the time interval between them and also computes and stores the average air pressure during each of these periods. Note that this was only done for periods when the geyser was active.

We use the natural logarithm of refill time (Figure 4) and heating time (Figure 5). This is because it seems reasonable to assume an exponential relationship - as air pressure goes to infinity the time between two eruptions becomes infinite and as air pressure goes to negative infinity, the time between two eruptions goes to zero. The same applies to heating and filling times. Regression lines are fitted through the datasets.

The analysis shows that refill time and heating time do indeed depend to some extent on air pressure. If the assumptions used in measuring refill time and heating time are correct, then Figure 4 and Figure 5 show that about 30% of the variation in refill rate and 35% of the variation in heating rate can be explained by the variations in air pressure. In eruptive mode, about 40% of the variability in eruption frequency (the inverse of the time between two eruptions) can be explained by variations in air pressure.

2.3 Eruption frequency and air pressure

Using a slight variation of the algorithm developed in the previous section we can take the peaks of every cycle and calculate the time and average air pressure between them. For this analysis we look at the entire data collection.

Figure 6 shows a scatter plot of the log of eruption frequency against air pressure for all of the datasets combined.

From the linear regression line (R^2 = 38%), shows that only 38% of the variation in eruption frequency is explained by air pressure. Notice that it is not clear whether the relationship is linear since the data seems to fall off the line by a large amount as the pressure gets higher; this may have to do with the pressure threshold, so that we may get an asymptote at some unknown point, possibly close to 980 hPa.

2.4 The effects of rainfall

There is no consistent relationship between rainfall and spring temperature for all the datasets. However, there is possibly a relation between very high rainfall and low spring temperature between 17/01/2011 and 01/02/2011 (Figure 7). The temperature drops sharply then recovers twice, corresponding to two periods of high rainfall. After each event, the geyser's temperature goes through a recovery period to bring the system back into its original state.

2.5 Waiotapu Geyser Conclusion

From the analysis it is clear that air pressure is definitely a factor affecting the Waiotapu Geyser. Periods of high air pressure corresponded with the quiescent mode in the data and periods of low air pressure corresponded with the eruptive mode, and lowering the air pressure seemed to increase the temperature cycle's frequency. Quantitative testing showed that this accounts for 38% of the cycle frequency variability.

There is some evidence that variations in air pressure lead to variations in the filling and/or heating rates of the geyser and hence its eruption frequency. However, the correlation rests on the set of assumptions that were made.

Other unidentified factors are also likely to affect the system. In light of the previous studies on geysers (White, 1967; Steinberg *et al*, 1981; Ingebritsen & Rojstaczer, 1993, 1996; Rojstaczer *et al*, 2003; Husen *et al*, 2004; Hurwitz *et al*, 2008), they may include things such as tidal forces, the longer-term hydrologic cycle, the internal dynamics of the geyser, seismic events, and precipitation trends.

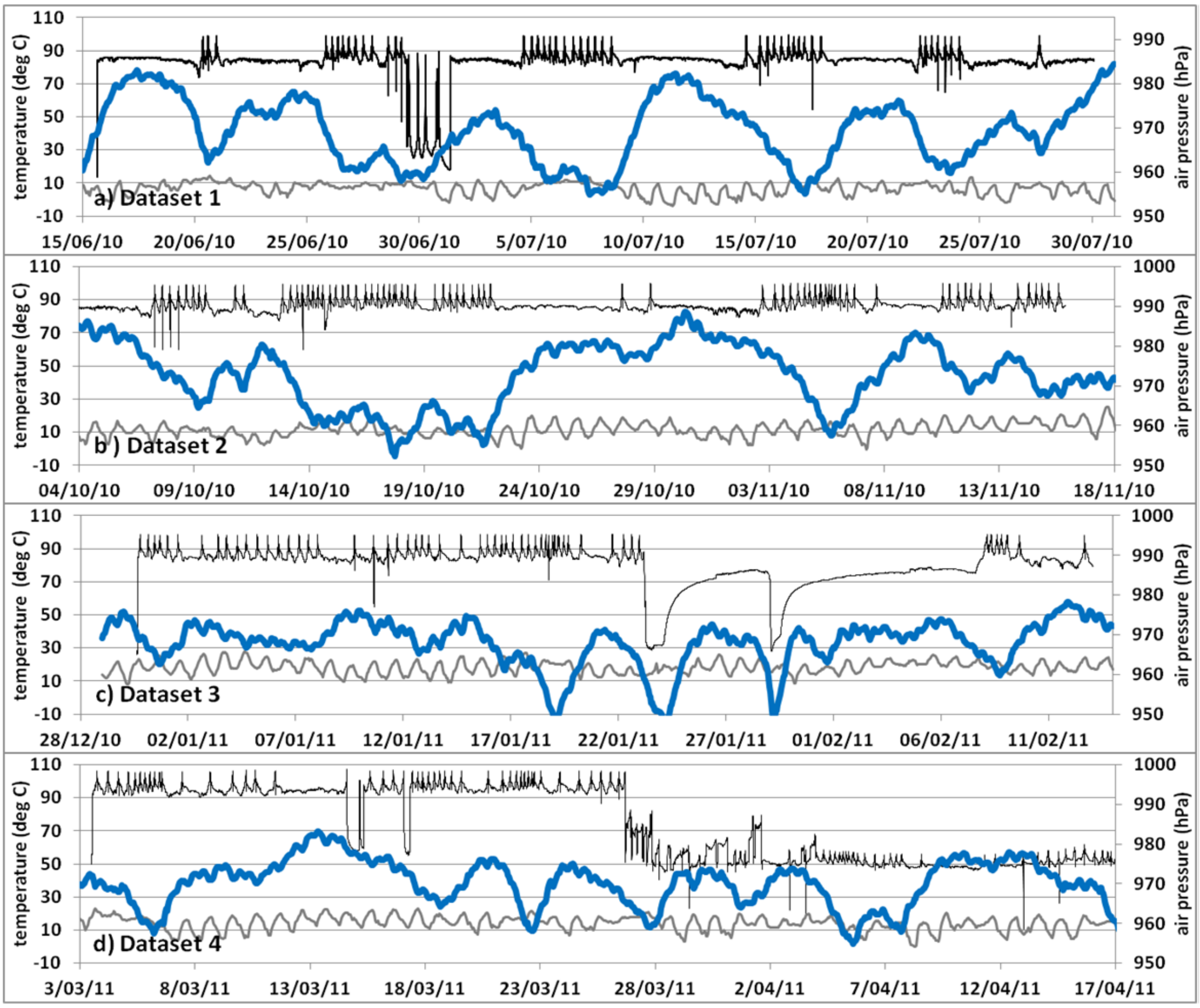

Figure 2. Spring temperature is plotted along with air pressure and air temperature. The grey line is the air temperature, the thick blue line is air pressure and the thin black line is spring temperature. Pressure (right axis) is measured in hectaPascals (hPa) while temperature (left axis) is measured in degrees Celsius (°C). (a) Dataset 1. (b) Dataset 2. (c) Dataset 3. (d) Dataset 4.

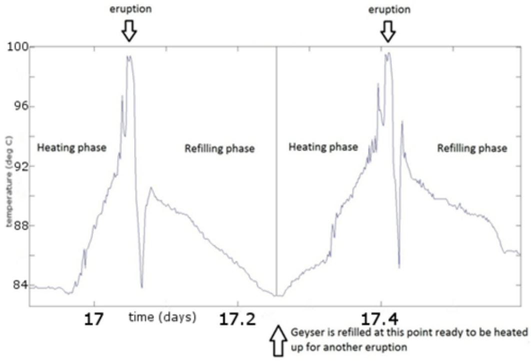

Figure 3. A typical cycle is broken into two phases: a refill phase and a heating phase. The eruption is treated as happening instantaneously at the peak of each cycle.

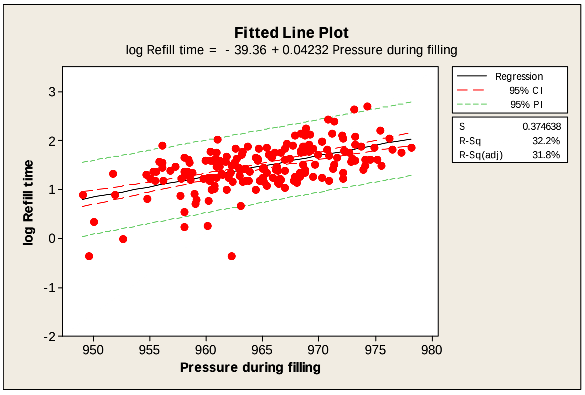

Figure 4. Log refill time versus air pressure.

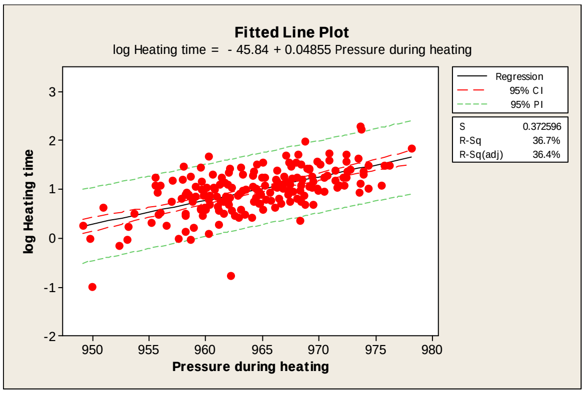

Figure 5. Log heating time versus air pressure.

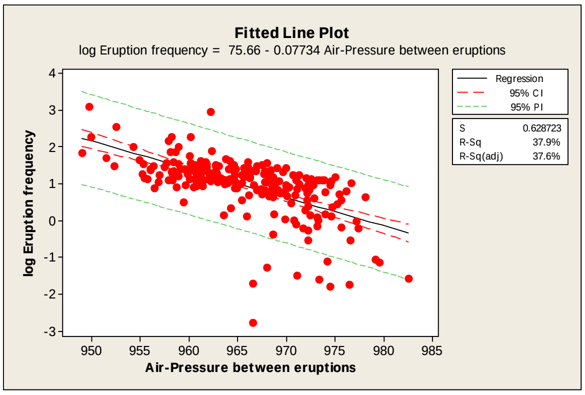

Figure 6. Log eruption frequency versus air pressure.

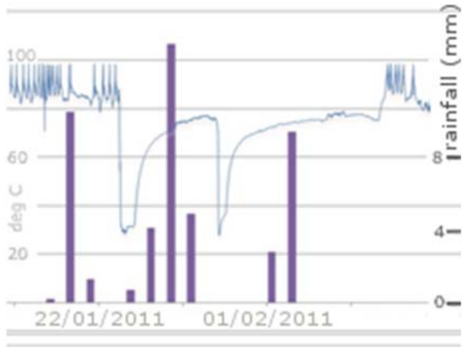

Figure 7. Spring temperature (°C) in blue and rainfall (mm) in purple. From Dataset 3.

3. SODA FOUNTAIN

3.1 Description of the data

The Soda Fountain is an "erupting hot spring" located at the Orakei Korako Geothermal Field. It consists of dilute HCO_3–Cl water with the water level rising and falling. The spring has had long dormant periods. Other springs in the area also show cyclic behaviour (Lynne & Howe, 2010; Newson, 2011).

Although difficult to see from the plots in Figure 9 due to the high frequency oscillations, the temperature shows periodic patterns. There are two main types of cycle, described below:

1. The temperature oscillates over approximately 5 °C, with an average temperature above 90 °C. These low-amplitude high-temperature intervals are used for the Fourier analysis.

2. There are periods when the temperature cycles between near-boiling and less than 70 °C; at times it drops below 40 °C. The process that causes this large fluctuation in the temperature is unknown, but it is possibly caused by the water level dropping below the level of the probe, meaning that the data consists of water temperature and air temperature measurements. Although this is one possible explanation, until further investigations can demonstrate the reason for the large fluctuations, the data cannot be used for Fourier analysis. However, it is reasonable to investigate any possible correlation between climatic factors and the interval of these large temperature fluctuations.

3.2 Effect of climate factors

The variability of the cycle amplitude in Datasets 1, 3, 4, and 5 make it difficult to characterize the continuous dataset. Figure 9 does not show any discernible relationships between any of the climate variables and spring temperature. However, because Dataset 2 has a regular cycle throughout 45 days, we have analysed the correlation between air pressure and spring temperature in following sections.

3.3 Effects of air pressure variations

Using the same algorithm as for the Waiotapu Geyser and applying it to the Soda Fountain Dataset 2 checks for the influence of air pressure on the cyclic behaviour of the spring. The regression analysis of the natural logarithm of the cycle frequency against air pressure again shows little correlation (Figure 8). Note that what we refer to as cycle frequency here is the inverse of the time between two peaks.

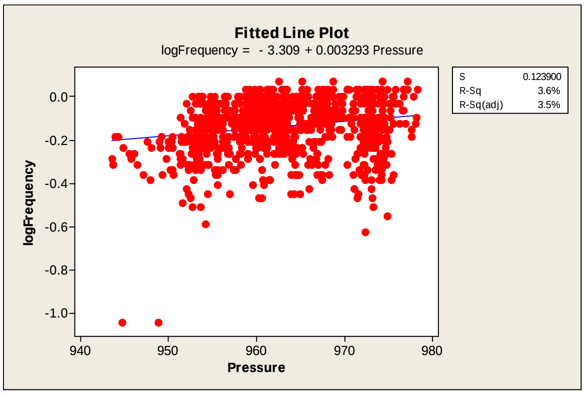

Figure 8. Log (frequency) against average air-pressure: regression plot.

3.4 Fourier analysis

In order to analyse the frequency components of the temperature cycles we used a Discrete Fourier Transform.

The datasets have been broken down into intervals which display regular cyclic temperature variation of less than 10 degrees, and a high average temperature (greater than 90 °C) shown in Figure 10(a) to (h). This ensures that the analysis is applied to water temperature, and not to intervals where the datalogger may have recorded air temperature over part of the cycle as discussed in the previous section. This provides eight suitable time intervals; as shown in Table 1. The data details and results of the analysis are given in Table 1 and shown graphically in Figure 11.

Table 1. Details and Results of Fourier analysis for all datasets.

	Interval	Length (days)	T_{av} (°C)	Dominant frequency (cycles/hr)	Length of cycle (hr)
Dataset 1					
Subset 1	25/06/2010 - 02/07/2010	7	92.9	1.02	0.98
Dataset 2					
Entire dataset	15/08/2010 - 29/09/2010	45	91.1	0.94	1.06
Dataset 3					
Subset 1	04/10/2010 - 08/10/2010	4	94.0	0.78	1.28
Subset 2	22/10/2010 - 28/10/2010	6	97.6	0.42	2.38
Subset 3	14/11/2010 - 16/11/2011	2	102.0	0.33	3.03
Dataset 4					
Subset 1	31/12/2010 - 07/01/2011	7	95.4	0.38	2.63
Dataset 5					
Subset 1	04/03/2011 - 18/03/2011	14	94.0	0.16	6.22
Subset 2	05/04/2011 - 17/04/2011	12	107.0	0.28	3.58

3.5 Soda Fountain Conclusion

No effects due to air temperature, air pressure, rainfall or seismic events on the Soda Fountain were identified.

A Fourier analysis of temperature data from the Soda Fountain shows that for the time intervals sampled, the temperature cycle was between one and six hours, with an average temperature between 91 and 107 °C. The maximum temperature reaches 120 °C in Dataset 5. There are no observations of whether the spring was geysering at the time, but if the temperature recording was accurate, there is a possibility that this could be a period of geysering.

The cause of the cycling is not known. It may be due to the spring's own internal dynamics, other nearby springs or other, as yet unidentified, factors. The adjacent Lake Ohakuri has daily water level changes. Due to time limitations, this study has not assessed the effect of these lake level variations, but in future they should be taken into account.

There are intervals during which the water level in the spring shows large fluctuations. We suggest that the water level fell below the probe level and the minimum temperature measurements were of air, rather than water, temperature.

4. DISCUSSION

This study applies a quantitative approach to geothermal temperature time series, which has demonstrated a relationship between air pressure and spring activity, and identified the dominant frequencies in cyclic data. There are also lessons for designing future monitoring programs which are briefly discussed below.

There may also be a longer-term response to hydrologic or climatic conditions which cannot be identified with short, discrete, datasets. Continuous data would show, for instance, if there is any seasonal component in activity.

Future data collection should include water-level or pressure information. This would enable a better interpretation of temperature data.

These springs were chosen because they showed cyclic temperature variation. Datasets from more springs in the same area would show if cyclic behaviour can be related to spatial proximity, or other spring characteristics such as water chemistry (using chemistry as a proxy for water source); it may be that cycle characteristics are different for every spring showing regular temperature variations.

This study is based on temperature time series taken from a single point in each spring. If it is possible to obtain temperature data from multiple levels in the feed channel (spring vent), this may give information on processes in the channel (for instance boiling, and/or location and timing of inflows).

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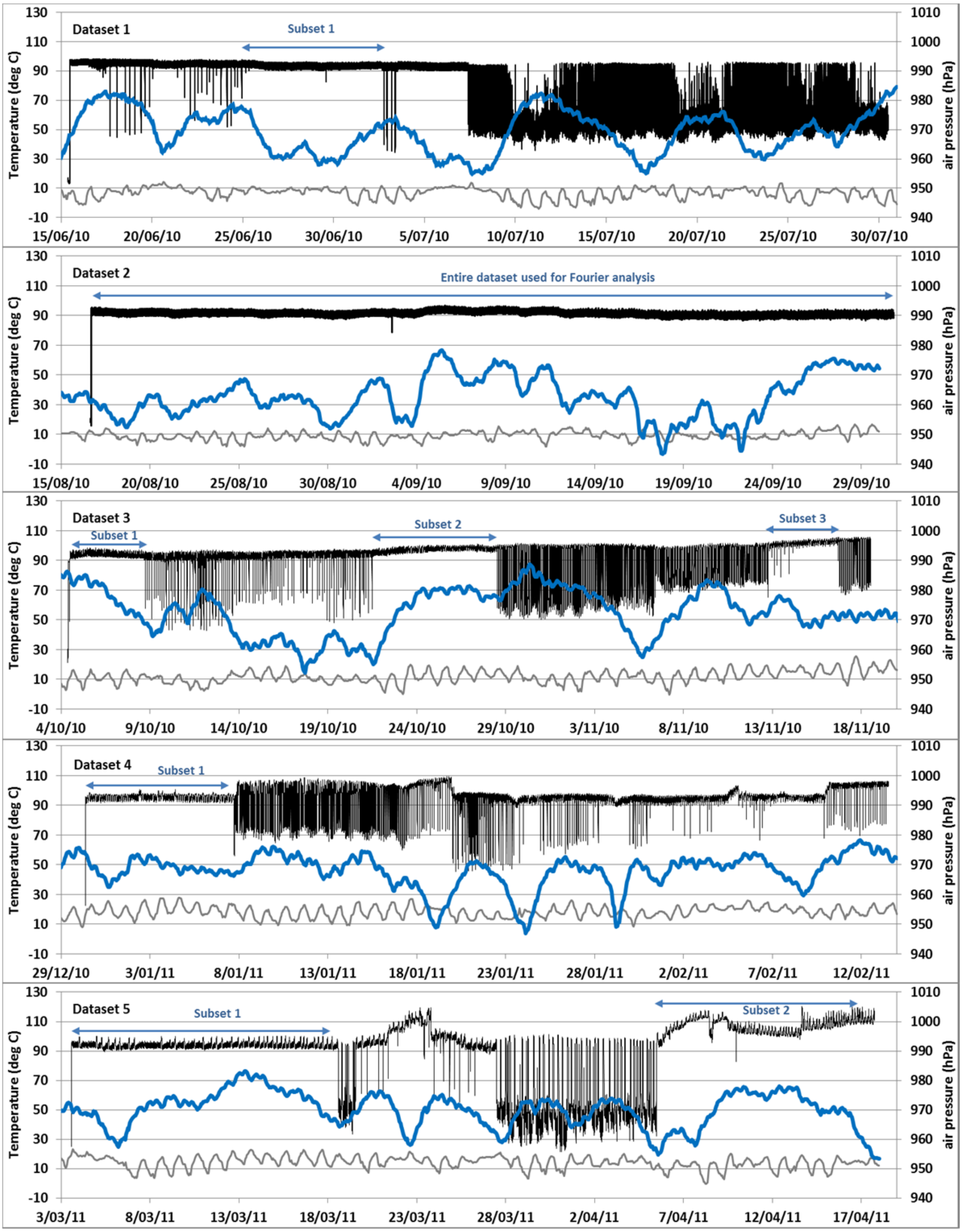

Figure 9. Soda Fountain spring temperature, air pressure and air temperature as time series. In each case, the grey line is the air temperature, the blue line the air pressure and the black line is spring temperature. Pressure (right axis) is measured in hectoPascals (hPa) while temperature (left axis) is measured in degrees Celsius (°C). Subsets of the data that are used for the Fourier analysis are indicated by the blue arrows.

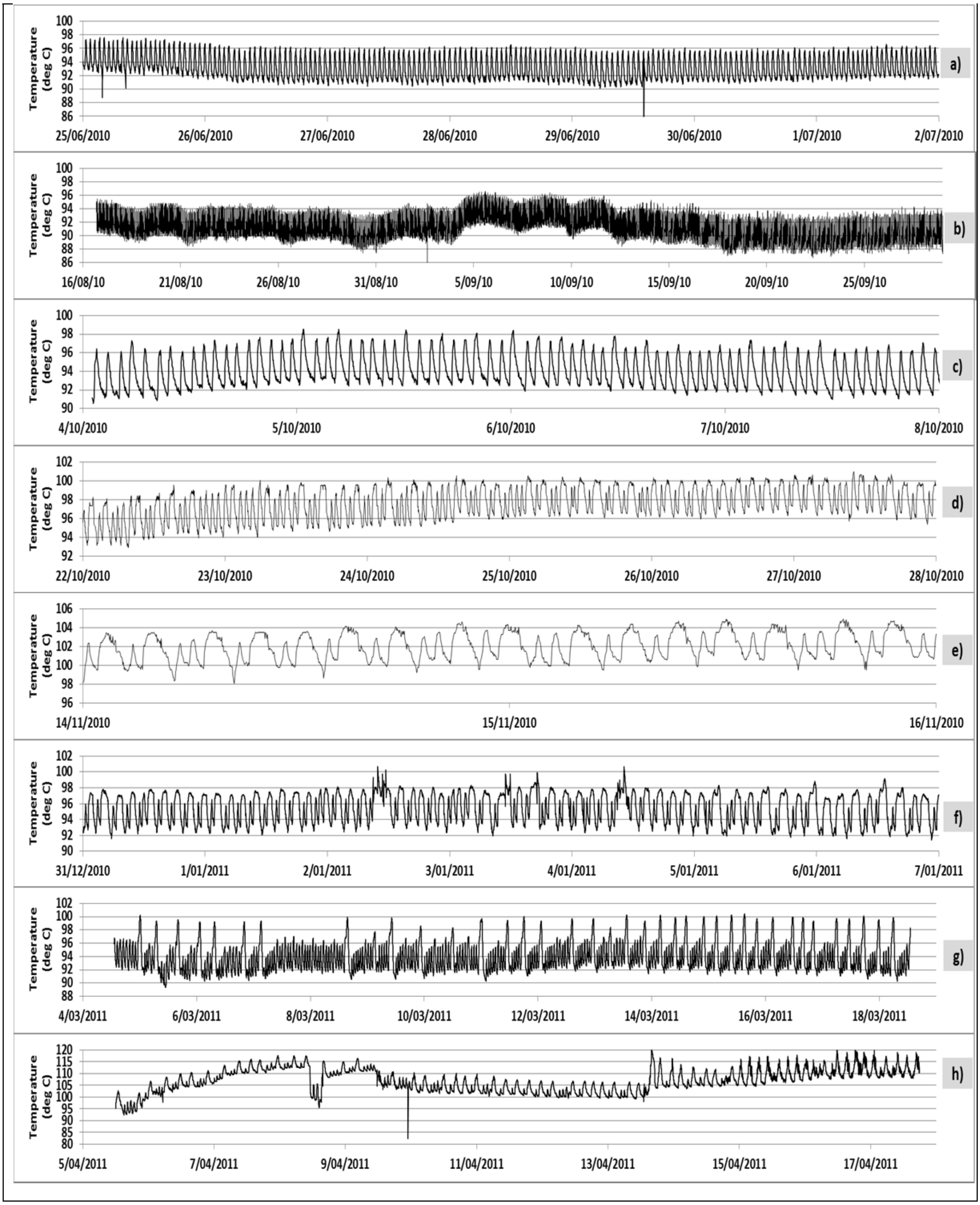

Figure 10. Plots of the subsets of Soda Fountain Datasets that have regular temperature variation and are suitable for a Fourier analysis. The entire dataset for Dataset 2 is suitable, while Datasets 1, 3, 4, and 5 have shorter time intervals within each dataset. (a) Dataset 1, Subset 1. (b) Dataset 2, entire dataset. (c) Datset3, Subset 1. (d) Dataset 3, Subset 2. (e) Dataset 3, Subset 3. (f) Dataset 4, Subset 1. (g) Dataset 5, Subset 1. (h) Dataset 5, Subset 2.

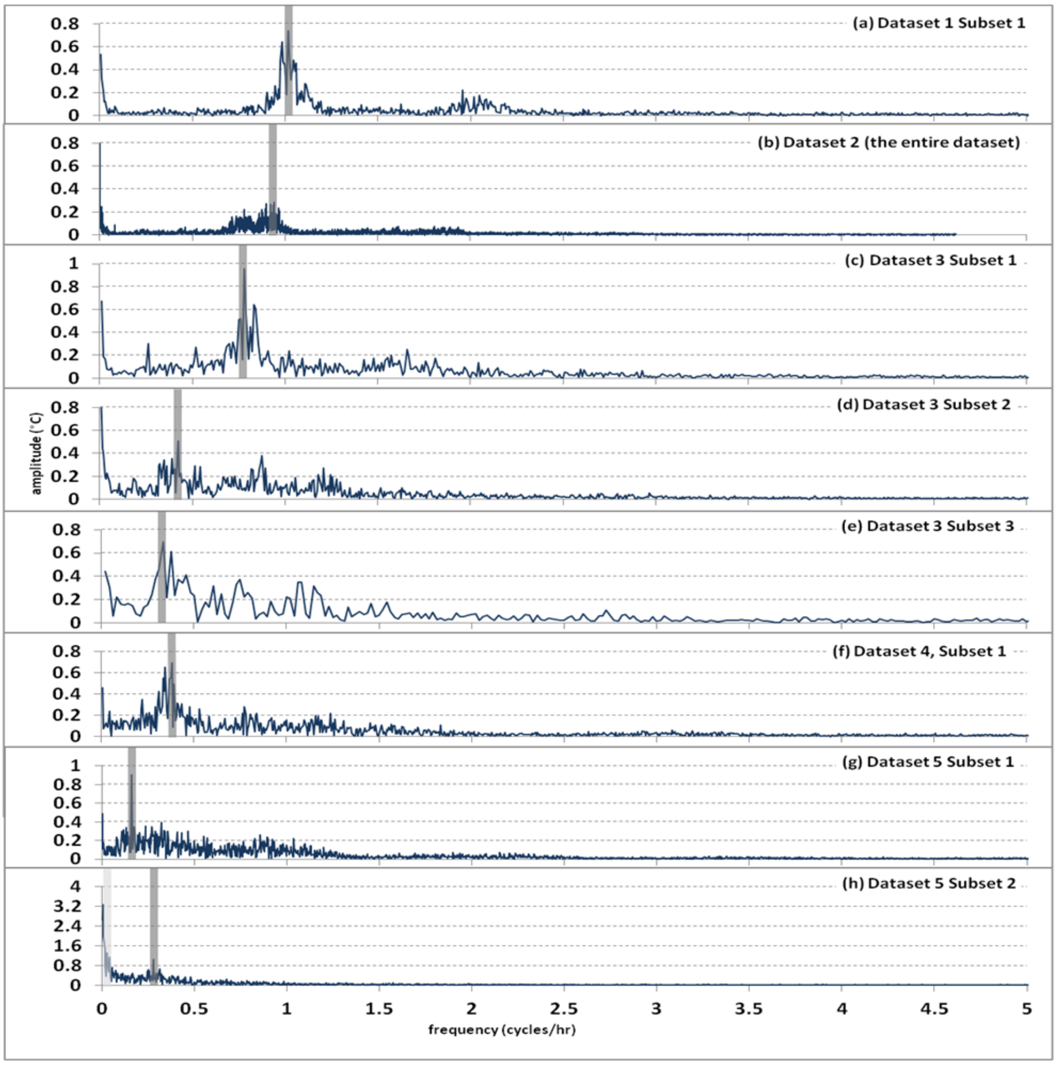

Figure 11. Frequency vs amplitude from the Fourier analysis. The vertical line highlights the dominant frequency for each dataset (also see Table 1). Note that Dataset 5 Subset 2 has a large amplitude, low frequency component, highlighted here by a very light grey line. The frequency of interest, that is comparable to the other datasets, is highlighted by the darker grey line.

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