Troglofauna Habitat Data Analysis
June 2017

Prepared for
Rio Tinto

astron

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Abbreviations

Abbreviation	Definition
C	Celsius
df	Degrees of Freedom
F	F statistic
m	Metre
MEA	Mesa A
MEB	Mesa B
MEK	Mesa K
RH	Relative Humidity
SD	Standard Deviation

Executive Summary

Astron Environmental Services was requested to undertake statistical analysis of a set of downhole temperature and relative humidity data from uncased drill holes at Mesa A, Mesa B and Mesa K collected by Rio Tinto Iron Ore between 2009 and 2017. The aim of this analysis was to test for impacts of mining at Mesa A on down hole temperature and relative humidity – variables which may delimit troglofauna habitat. This included the following tasks:

- carry out a literature review regarding the microclimatic requirements and thresholds for troglofauna
- assess the quality of extensive longitudinal data
- identify any significant issues associated with the data
- provide solutions to resolve any identified data issues
- test for significant changes in microclimate variables that may be associated with impact from mining
- test for significant relationships between surface microclimate data and down hole data.

Due to issues with temperature and humidity probe function, only data collected post 2013 was analysed. This led to the exclusion of any categorical pre-impact post-impact analysis at Mesa A, as productive mining commenced in February 2010. The analysis identified clear step changes throughout the data set and these were thought to be associated with probe maintenance. Analyses were applied to the data without these step changes being adjusted. However, the following conclusions were reached:

- Proximity to the Mesa A pit edge did not influence mean subterranean temperatures or humidities.
- With increased proximity to the Mesa A pit edge, humidity became more variable, and more strongly resembled a sinusoidal pattern of temporal change, based on an annual cycle. Increasing strength of sinusoidal curves could potentially indicate an increased connectivity with surface climate. However, some of the highest values for variation in humidity were observed approximately 100 m from the pit edge and these values were not explained by probe depth. Variation observed is also within the error margins of probes at high humidity (±5% RH at 100% RH).
- In comparison to other sites (Mesa B and Mesa K), Mesa A did not demonstrate significantly different variation in humidity values or temperature values or their fit to sinusoidal curves.
- Temperature and humidity at Mesa A have not changed significantly over time since January 2014. This lack of change is reflected in stable surface temperatures and humidity over the same period.

Activity at the Mesa A mine site has had little discernible influence on subterranean climate.

Improvements to data through adjustment at step changes known to be associated with probe maintenance may improve confidence in these conclusions.

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1 Introduction

1.1 Background

1.1.1 Troglofauna Habitat Analysis

Astron Environmental Services was requested to undertake statistical analysis of a set of downhole temperature and relative humidity data from uncased drill holes at Mesa A, Mesa B and Mesa K collected by Rio Tinto Iron Ore between 2009 and 2017. The aim of this analysis was to test for impacts of mining at Mesa A on down hole temperature and relative humidity – variables which may delimit troglofauna habitat. This included the following tasks:

- carry out a literature review regarding the climatic requirements and thresholds for troglofauna
- assess the quality of extensive longitudinal data
- identify any significant issues associated with the data
- provide solutions to resolve any identified data issues
- test for significant changes in subterranean microclimate variables that may be associated with impact from mining
- test for significant relationships between surface climate data and down hole subterranean data
- attend meetings with Rio Tinto staff to discuss data characteristics and to summarise findings.

1.1.2 Subterranean Climates and Troglofauna Habitat

The aim of this section is to review available literature related to environmental variables which describe subterranean habitats, and delimit the environmental requirements of troglofauna. One aim was to find critical information regarding troglofauna microclimate requirements that could be related to any significant change in microclimate recorded in the project's field probes.

Much of the literature pertaining to subterranean climates focuses on the opening of caves to tourists (for example, Cigna 2002), in contrast to the small scale subterranean habitats studied here. However, the furthest, most isolated recesses of caves in which obligate troglofauna live are usually characterised by complete darkness, constant temperature and high humidity (Poulson and White 1969; Howarth 1980; Howarth 1993). Humidity is often at saturation point (Howarth 1983, 1980; Howarth 1993). Many authors describe a stable temperature equivalent to the mean surface temperature (Clarke 1997; Holsinger 1988). However this is usually stated anecdotally free of supportive data, which have remained elusive; it is not known how widespread this relationship with surface temperature may or may not be. These descriptions of cave microclimates have been widely propagated, but there is presently no integrated study of microclimate in subterranean habitats over a range of geographic regions (or the published data available to compile such a study).

Depending upon the level of connectivity to surface conditions, microclimate may display a sinusoidal pattern of variation, based on an annual cycle (Cigna 2002; Jury and Horton 2004). This cycle is usually lagged based on the rate of propagation from the surface (Cigna 2002) and climate change at the surface may take several years to be reflected in the cave habitat (Mammola, Goodacre, and Isaia 2017).

Obligate troglofauna are often evolved from tropical terrestrial taxa or those otherwise adapted to moist habitats such as leaf litter. As climates have dried, troglofauna have found refuge in cave habitats and adapted further to their particular conditions as described above. Given the constant environmental conditions, troglofauna tend to have lost their abilities to regulate water loss (Humphreys and Collis 1990; Hadley, Ahearn, and Howarth 1981; Ahearn and Howarth 1982; Howarth 1983; Bull and Mitchell 1972; Mammola and Isaia 2017), and have adapted to live at saturated humidities through mechanisms such as high integument permeability. Troglofauna have also reduced thermoregulatory mechanisms (Rizzo et al. 2015). As a consequence, water loss is generally higher in troglofauna than their surface dwelling relatives, whilst their tolerance to different or variable temperature may be limited (Poulson and White 1969; Rizzo et al. 2015). Howarth (1983) suggests that the "most critical environmental factor governing [troglofauna] distribution appears to be the stable saturated atmosphere" and that troglofauna live in a virtual aquatic environment where water loss ceases to be an ecological challenge. It can therefore be expected that decreases in humidity below saturation, and changes to temperature could significantly affect troglofauna survival and/or distribution.

2 Methods

2.1 Data Overview

The total monitoring dataset consisted of data from 44 stations: 25 at Mesa A, three at Mesa B, 10 at Mesa K and six 'mobile' stations at Mesa A (Appendix A). Data were usually logged from 2011 to 2017 at Mesa A, while Mesas B and K were usually monitored from 2012. One of the monitoring stations at Mesa K (MEK09) appears to have entirely failed, having only recorded a small amount of unreliable data in 2012. Temperature and relative humidity was recorded at hourly intervals at all sites. Temperature and humidity probes were paired at individual stations and were placed at a variety of depths, from 5 m to 25 m. Capacitive sensors were used to monitor relative humidity.

2.2 Data Quality Control

Data from each station were initially assessed visually. Step changes, generally considered to be a consequence of probe maintenance (Rio Tinto Iron Ore 2014) are apparent throughout the data set.

At many stations, particularly where values are relatively consistent, a clear disjunct between pre and post 2014 data is visible. This is due to substantial improvements to the monitoring configuration at this point. Issues with probes prior to 2014 are well described in Rio Tinto Iron Ore (2014). The primary issue was the internal heater in the relative humidity probe interfering with measurement made by the attached temperature probe. This not only led to inaccurate temperature records but consequently led to miscalculation of the relative humidity records. Higher variation in temperature records in general is visible in plots of the data. This variation is less apparent in the humidity readings, although the pre/post January 2014 disjunct is still visible. As a consequence of this issue, which is not easily addressed through individual recalibrations of data, pre 2014 data were removed prior to all analyses for the purposes of this assessment. Pre 2014 temperature data could potentially be improved by a combined approach of removing data that is known to be heated and adjusting for known probe changes. As the heater is likely to be activated relatively frequently, and there are no strict criteria to enable the detection of a heating period, this is likely to be impracticable.

Data were not adjusted as a consequence of step changes associated with any probe maintenance that occurred post January 2014. This is discussed further in Section 4.

Temperature values were occasionally clear aberrations (usually temperature of 300°C or 0°C), so temperature values included in the analysis were restricted to less than 50°C and more than 10°C (datasets displayed in Appendix B have these data removed). This did not appear to remove any 'real' values. 'Real' values are characterised by a gradient in temperature change rather than a sudden step change.

Humidity probes generally do not function accurately near the point of saturation (100% relative humidity (RH)), with accuracy lost when RH reaches around 95% (Cigna 2002; Rio Tinto Iron Ore 2014, R. Vlad pers comms June 2017). Humidity probes at Mesas A, B and K frequently recorded values higher than 100%. Humidities over 105% probably indicate probe failure (for example, damage from corrosion) while values of 100% to 105% should be considered to be 100% (Rio Tinto Iron Ore 2014, R. Vlad pers comms June 2017). In terms of accuracy, values between 95% and 100% could be considered to be at least 95% RH. Cigna (2002) note the difficulties with use of capacitive sensor devices in high humidity environments. As a consequence of these issues, all RH values from 100 to 105% in the post January 2014 data set were changed to 100% and values above 105% were excluded.

Data from the six 'mobile' sites located within Mesa A (Appendices C and D) were plotted but were not analysed further as they were not well integrated into the spatial designs described below.

2.2.1 Timing of Potential Disturbance within Mesa A

Aerial imagery spanning the period from 2001 to 2015 was provided and used to estimate the timing of potential impacts from the mining of Mesa A. The northern portion of the south-western section of the mine (circa stations MEA06 and MEA07) was cleared in late 2013, while the rest of the mine was cleared between December 2009 and April 2011 (there is a lack of imagery spanning this period). A caveat in defining these dates is that aerial imagery can only identify the initial clearing event. It is possible that changes to subsurface temperature and humidity require a threshold amount of material to be removed or clearing to occur; this can't be inferred from the aerial imagery.

2.3 Analysis

2.3.1 Testing for Potential Impact

As pre 2014 data was considered to be currently unreliable, no categorical pre impact/post impact comparisons were possible (linear regression models are used to assess temporal changes due to ongoing impacts post initial clearing). Instead of a pre/post impact assessment, location was the primary factor used to approximate the level of potential impact from mining activities. Space was represented by two components: distance from mine pit within Mesa A, and secondly, site type, with Mesas B considered a control site and Mesa A the potential impact site. Mesa K was also included in the analysis as it is inactive and was mined prior to 2010.

Variables analysed were:

- Mean levels of humidity and temperature, with the expectation that disturbance would lead to a decrease in humidity and a change in temperature (it is not necessarily clear in what direction; discussed further below).
- Mean levels of variation in humidity and temperature, with the expectation that disturbance from mining would expose habitats to surface climate, therefore increase the level of variation.
- Goodness of fit to sinusoidal curves which describe a pattern of regular oscillation on an annual cycle. Explained in detail below.

2.3.2 Sinusoidal Curves in Climate Data

With increased exposure to surface climate, subterranean microclimate takes on an increasingly sinusoidal pattern, based on a 12 month cycle (Cigna 2002). This exposure will increase with decreasing depth or other processes such as contrasts in substrate materials which expose habitats to external surface climate. Once the influence of probe depth has been controlled for, disturbance is expected to increase the amplitude of climate data, with the data fit to a sinusoidal curve increasing with proximity to significant disturbance. Data fit to a sinusoidal curve was quantified using the R^2 values based on an individual model for each probe. R^2 values indicate the proportion of variation in the response variable that is explained by the predictor variable, with a zero value indicating no variation is explained, and 1 indicating that all variation is explained. This approach is quite powerful as it differentiates between model fits to a sinusoidal curve despite unexplained step changes in the data because the sinusoidal curves are expected to remain in the data despite step changes.

2.3.3 Statistical Relationships with Potential Disturbance

The relationship of each climate variable to distance from the Mesa A mine pit was tested using a linear model with probe depth included as a model covariate. This covariate was used to control for the effect of probe depth before considering any effect of distance to mine pit. Distance to the mesa escarpment was not included in the model as it was negatively correlated with distance to the mine pit – as distance from the mine pit increased, distance from the escarpment decreased. Mean humidity, mean temperature, the variation of these two variables and their fit to sinusoidal curves were then regressed against distance and depth using a linear model, with significant relationships based on F values and considered significant at $P < 0.05$. Variables were calculated for the period beginning 1 January 2014.

Appropriateness of models was examined by testing the normality of the model residuals. This occasionally led to transformation of the data (usually log transformation). If data transformation was insufficient, a similar analysis using a non-parametric approach using bootstrapping was carried out using the R package “np”. In these instances, F values were not produced; only P values.

2.3.4 Changes Over Time

In order to test whether the subterranean temperature or humidity at Mesa A was changing over time following the initial mining impact, a linear regression was fitted to each probe data set. The slopes derived from these models were then compiled, and plotted against distance from the Mesa A mine pit. A linear model was used to test this relationship, with the test of the intercept parameter indicating whether the mean of all the slopes was significantly different from zero (that is, uniformly changing over time), while a significant slope would indicate an increased rate of change closer to the mine pit.

2.3.5 Comparison with Control Sites

Climate variables at Mesa A were also compared to sites considered to be non-impact control sites: Mesa B is completely intact and unmined, while Mesa K is inactive and was mined prior to 2010. Mesa A probe locations were further divided into three distance classes, based on distance to the mine pit and even distribution of points amongst classes: close (less than 40 m), medium (40 m to 60 m), far (more than 60 m from the mine pit). Difference amongst the mean values of the climate variables were tested using a linear model which included probe depth as a covariate and site as categorical variable. Climate variables tested were temperature, humidity, the standard deviation of these variables, and their individual fit to sinusoidal curves.

2.3.6 Subterranean Climate’s Relationship with Surface Climate

Understanding the link between the climate of subterranean habitats and surface climate is most informative when a temporal change in subterranean climate could potentially be associated with local disturbance, but could otherwise be associated with changes in surface climate. With a lack of pre versus post impact data and no indication that subterranean climate is changing significantly (see below; Section 3.2 Changes over Time), this type of investigation was less essential. However analysis of the relationship is included in order to investigate whether surface climate is in fact changing and to further understand the relationship between surface and subterranean climate.

The strength of the connection of surface and subterranean climate was also investigated by examining the goodness of fit of data to sinusoidal curves (Section 2.3.2 Sinusoidal Curves in Climate Data) in which the interplay of depth and potential disturbance is considered.

Surface climate data was provided in two formats: hourly intervals, recorded at the Mesas A and K Weather Stations from August 2011 to May 2017 and at daily intervals recorded at Mesa J Weather Station from February 2008 to May 2017. Analyses focused on temperature and relative humidity using the hourly data set.

Correlations between subterranean and surface climate were tested using linear models, with and without a lag period. Appropriate lag periods were estimated visually, prior to comparing the R^2 values of the two models.

Rather than assess the variation in all stations, two stations with contrasting depth and particularly reliable data (assessed visually, based on the number of step changes and evenness of temperature and humidity variation over time) were compared. Station MEA11 (5 m depth) was most clearly connected with surface climate, based on the strength of a fitted sinusoidal curve, while station MEA02B (22 m depth) was one of the deeper probes with particularly consistent data, and exhibited very little cyclical variation in data.

All analyses were performed in R (R Development Core Team 2016).

3 Results and Discussion

The analysed data, presented by individual probes is provided in its full form in Appendix C (January 2011 to May 2017; extreme outliers in temperature and humidity values have been removed in order to improve figure resolution) and in its truncated form with all outliers removed in Appendix D (January 2014 to May 2017).

3.1 Potential Disturbance within Mesa A

Mean subterranean temperature and humidity did not vary with proximity to the Mesa A mine pit (Figure 1a and b, Table 1), and these values did not vary with probe depth (Figure 2a and b, Table 1). While the variation (quantified by standard deviation) in temperature did not differ significantly with proximity to the mine pit (Figure 1c, Table 1), the variation in relative humidity varied significantly, with higher variation closer to the mine pit (Figure 1d, Table 1), although the highest levels of variation are seen at intermediate distances (105-125 m; Probes MEA03B and 3C). The goodness of fit of temperature to a sinusoidal curve was not associated with proximity of mine pit (Figure 1e), but was associated with probe depth (Figure 2e). The humidity goodness of fit to a sinusoidal curve was associated with proximity to the mine pit (Figure 1f), but not probe depth (Figure 2f, Table 1).

Variation in humidity which may be associated with proximity to the Mesa A mine pit is reasonably low at approximately 1.25% RH (SD) and 4% RH (SD) in the highest case. This is within the bounds of probe error (± 5% at 100% RH) when probes are used at such high humidity.

Table 1: Summary of statistical results examining the statistical relationship between probe depth and distance from the Mesa A mine pit, and climatic variables. A linear model with probe depth and distance to mine pit as continuous variables was employed. SD = Standard deviation. P values in bold indicate statistical significance (P < 0.05). The Model fit is expressed in terms of the total variation explained by the model.

Variable	F	df	Model fit	P, probe depth	P, dist to mine
Temperature	1.3	2, 21	0.03	0.12	0.45
Humidity	0.76	2, 21	0.02	0.35	0.72
SD of temperature	#	#	#	0.10	0.90
SD of humidity	2.56	2, 21	0.12	0.95	**0.046**
Temp R^2 fit to sinusoidal curve	4.84	2, 21	0.25	0.007	0.83
Humidity R^2 fit to sinusoidal curve	2.20	2, 21	0.09	0.35	**0.049**

Test performed using a non-parametric approach involving bootstrapping. F values are not produced.

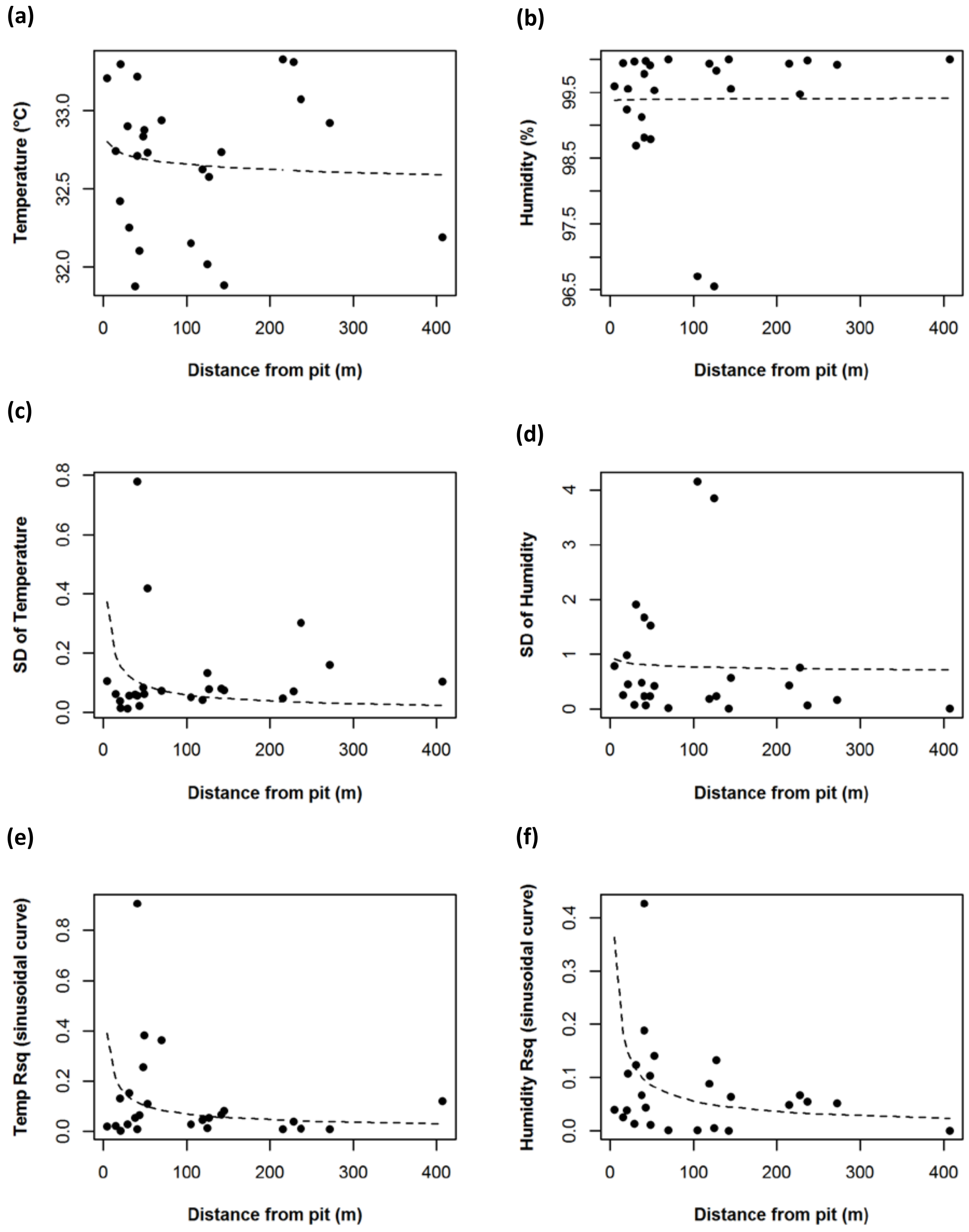


Figure 1: Relationships between probe distance from the Mesa A mine pit and microclimate variables. Figures a and b show the mean temperature and humidity values and their relationship with distance from the pit. Figures c and d show the level of variation around these mean values as quantified by the Standard Deviation. Figures e and f show the potential tendency of the temperature and humidity to oscillate sinusoidally given increased proximity to the mine pit edge. The R^2 values are the measure of goodness of fit to a sinusoidal curve based on an annual cycle.

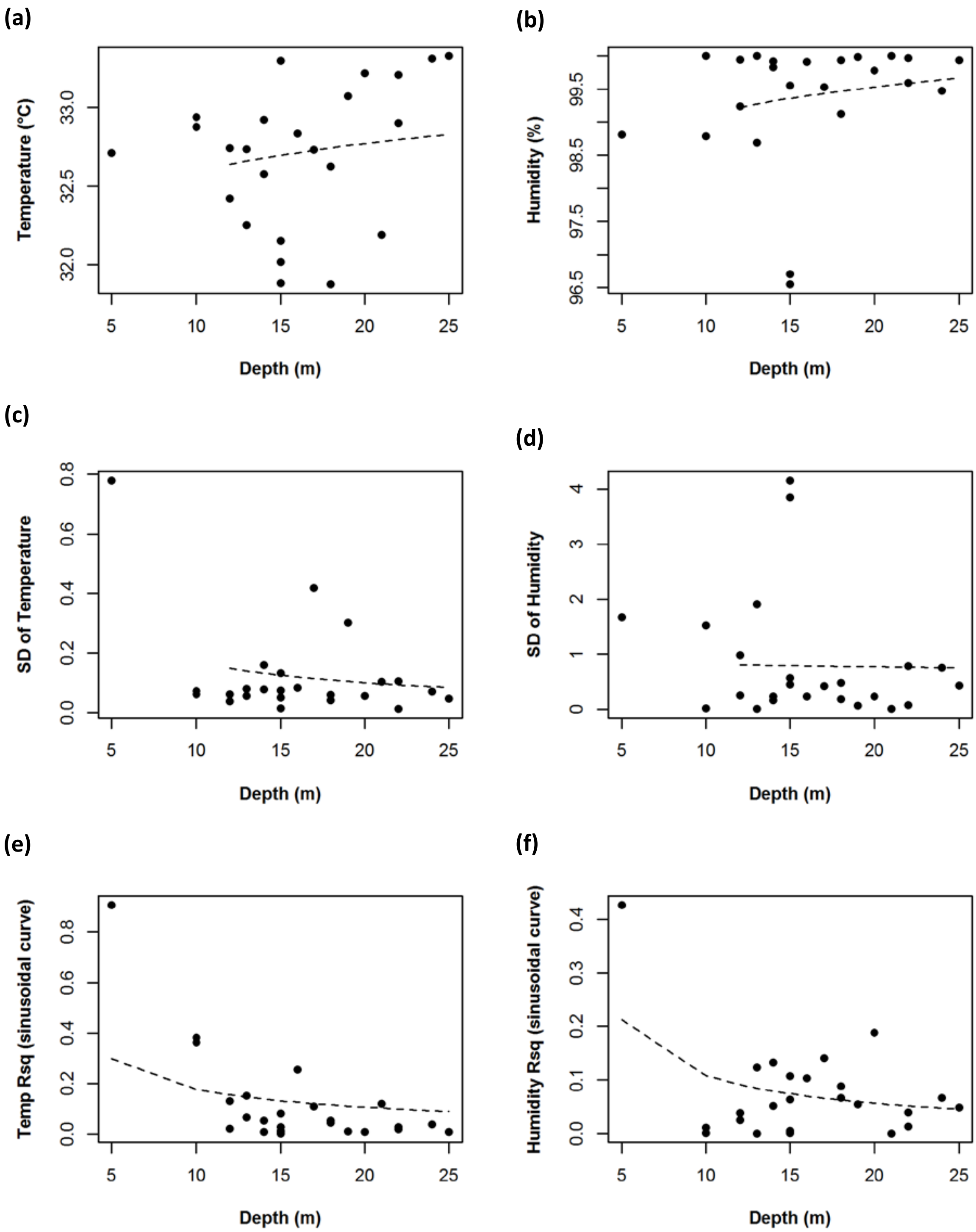


Figure 2: Relationships between probe depth and microclimate variables. Figures a and b show the mean temperature and humidity values and their relationship with depth. Figures c and d show the level of variation around these mean values as quantified by the Standard Deviation. Figures e and f show the potential tendency of the temperature and humidity to oscillate sinusoidally given decreased depth. The R^2 values are the measure of goodness of fit to a sinusoidal curve based on an annual cycle.

3.2 Changes over Time

There is no indication that the subterranean climate at Mesa A is changing significantly (Figure 3). The average slope of the change in temperature and humidity was not significantly different from zero (P = 0.68 and 0.36, respectively), and this slope (change in temperature or humidity with time) does not change with proximity to the mine pit (P = 0.95 and P = 0.42, respectively).

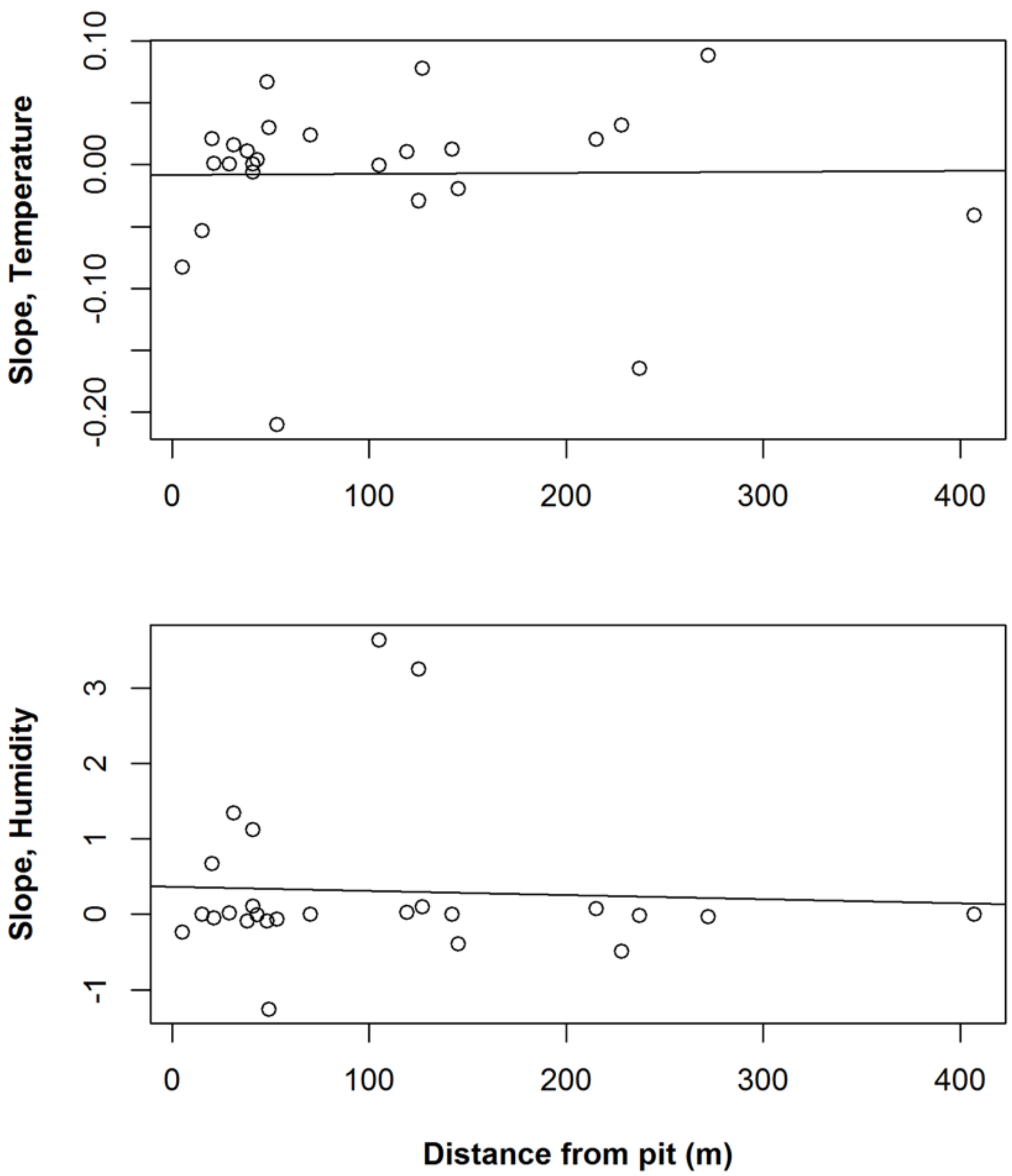


Figure 3: Relationships between distance from the Mesa A mine pit and the rate of change in temperature and humidity over the monitoring period (2014- 2017), based on the slope of linear regressions fitted to data for each probe. Lines are the lines of best fit, based on linear regression. For both temperature and humidity, their rates of change are not related to the distance from the pit.

3.3 Comparisons with Control Sites

Subterranean mean temperature differed significantly between sites, but this was due to Mesa K being significantly cooler than other sites. One suggestion is that Mesa K is more closely linked to surface climate due to previous disturbance due to past mining. However, there is no increased evidence of a sinusoidal pattern in the temperature data and the patterns at Mesa K are not significantly different to the other sites (Figure 4; confirmed by Tukey's pairwise test, P > 0.70).

Average surface temperature, based on the daily logged data was 27.3°C, which suggests, contrary to descriptions of other caves (see Section 1.1.2 Subterranean Climates and Troglofauna Habitat), that these subterranean systems are warmer than average surface temperatures. It is therefore assumed that disturbance which leads to increased connectivity with surface climate would lead to increased equilibrium with surface climate, and hence, a cooling of these subterranean habitats.

Standard deviation of temperature did not differ amongst sites, but differed with probe depth (Table 2, Figure 4), as expected based on increasing variation with increased exposure to surface conditions. Average humidity did not differ between sites and humidity did not exhibit significantly different levels of variation amongst sites or amongst probe depths (Table 2, Figure 4).

These results differ from the Mesa A analysis as the distances used in the previous analysis are truncated to three classes in the current analysis and hence variation within a distance class is lost in the categorical analysis.

Table 2: Summary of statistical results examining the statistical relationship between probe depth and site type (Mesa B, Mesa K and three distance classes at Mesa A), and climatic variables. The Model fit is expressed in terms of the total variation explained by the model. Temperature was significantly lower at Mesa K, while the fit of temperature to a sinusoidal curve was highest at Mesa K and the mid-range probes at Mesa A.

Variable	F	df	Model fit	P probe depth	Site type
Temperature	6.89	5, 30	0.46	0.50	**< 0.001**
SD of temperature	2.02	5, 30	0.13	**0.01**	0.53
Temp R^2 fit to sinusoidal curve*	7.23	9, 26	0.62	**< 0.001**	**0.03**
Humidity	1.12	5, 30	0.02	0.41	0.32
SD of humidity	1.08	5, 30	0.01	0.35	0.37
Humidity R^2 fit to sinusoidal curve	2.26	5, 30	0.15	**0.005**	0.68

* Includes a significant depth x site type interaction term (P < 0.001).

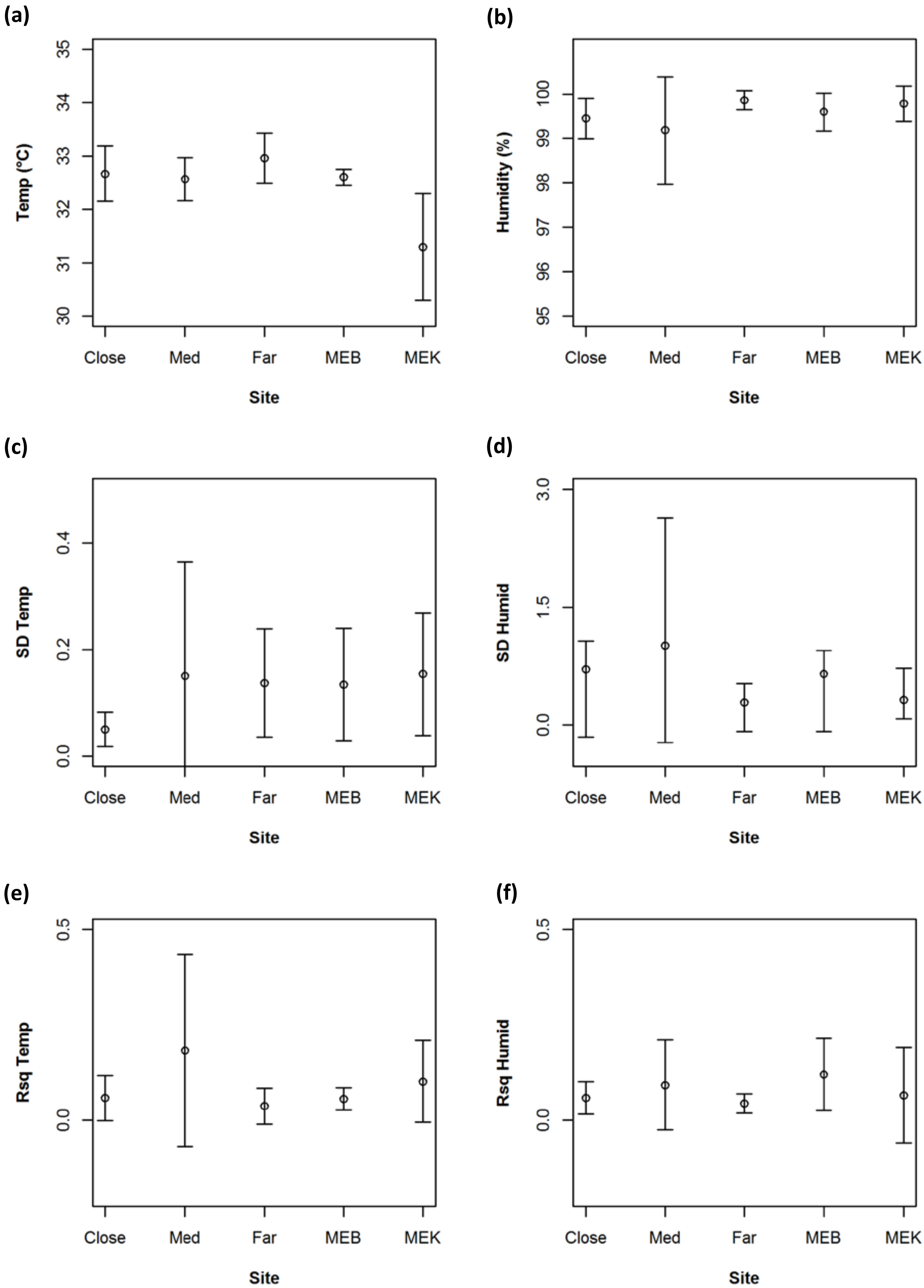


Figure 4: Comparison of climate variables amongst Mesa A distance classes with respect to the mine pit (close, < 40 m, Med, 40-60 m, far, >60 m), Mesa B (MEB) and Mesa K (MEK). Figures a and b show the mean temperature and humidity values across the five sites Figures c and d show the level of variation around these mean values as quantified by the Standard Deviation. Figures e and f show the potential tendency of the temperature and humidity to oscillate as quantified by the fit (R^2) to a sinusoidal curve. Error bars represent 1 SD.

3.3.1 Subterranean Climate's Relationship with Surface Climate

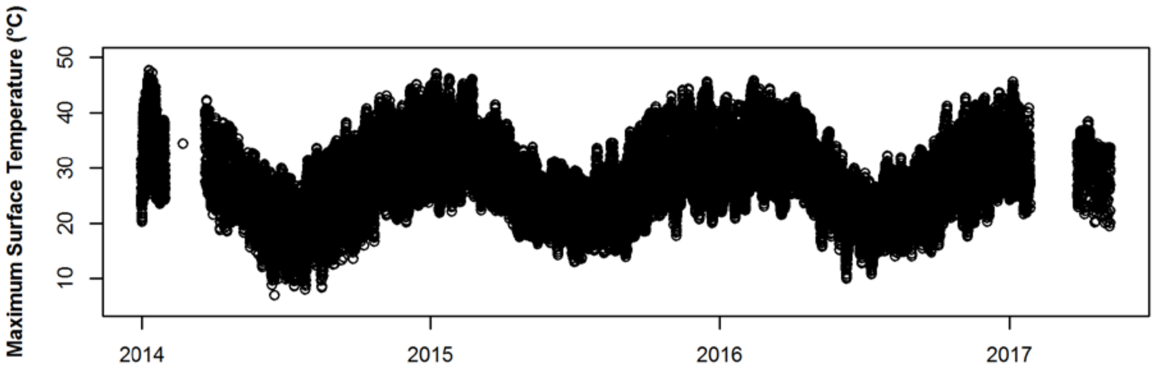
The relationship between subterranean temperature and surface temperature is dependent upon probe depth, contingent upon other variables such as soil profile and connectivity to surface climate (see Section 3.1 Potential Disturbance within Mesa A). As the most sensitive example, the MEA11 probe (5 m depth) follows the same annual sinusoidal cycle as surface temperature with the following modifications: the subterranean temperature cycle lags by an apparent four months (unlagged data, correlation R^2 = 0.006; lagged data, correlation R^2 = 0.316) and the variation in subterranean temperature (at 5 m depth) is one tenth that of the variation in surface temperature. As depth increases, the annual sinusoidal curve is dampened, and at, for example, a depth of 22 m, temperature is constant (Figure 6).

Change in surface temperature over time was analysed. The significant statistical relationship between surface temperature and time, ($F_{1, 26036}$ = 11.13, $P < 0.001$, $R^2 < 0.001$) is not unexpected give the extremely large number of samples and hence high statistical power. However, there was only a very weak relationship: The slope of the relationship would suggest that maximum hourly temperature declines by 0.004 degrees every 100 years, which is unlikely to be of practical significance and likely to be within error margins of monitoring equipment. MEA11 temperature has not changed significantly ($F_{1, 26061}$ = 0.7, $P = 0.40$, $R^2 < 0.001$).

Relative humidity is more complicated. Humidity increased over time at the surface ($F_{1, 25991}$ = 166.5, $P < 0.001$, R^2 = 0.006) and at the shallowest probe (MEA11, 5 m depth) ($F_{1, 21984}$ = 6762, $P < 0.001$, R^2 = 0.24). The humidity at MEA11 demonstrated an approximately sinusoidal response, with a 12 month cycle, which included an apparent nine month lag to surface humidity (Figure 7). However, the R^2 related to the correlation of the two humidity measures was not improved with this lag, probably due to the large amount of variation in the surface humidity data. Again, variation in subterranean climate (at 5 m) is approximately one tenth of that on the surface. At 22 m deep (MEA02B), variation in humidity is greatly reduced (Figure 8).

In summary, there is no evidence that subterranean climate changed between 2014 and 2017 (Figure 3) and while surface climate may be changing, these changes are very small compared with diurnal and annual temperature cycles and may be a result of high statistical power capable of detecting very small changes. The magnitude of annual variation of temperature and humidity is dependent upon depth, with an increasing association to surface climate with shallower depth (Figure 2). This relationship is contingent upon other variables such as soil profile and connectivity to surface climate. Lags between subterranean and surface climate are apparent. Although these lags appear to be 4 and 9 months long, they may in fact be much longer (for example, 16 and 21 month lags).

(a)



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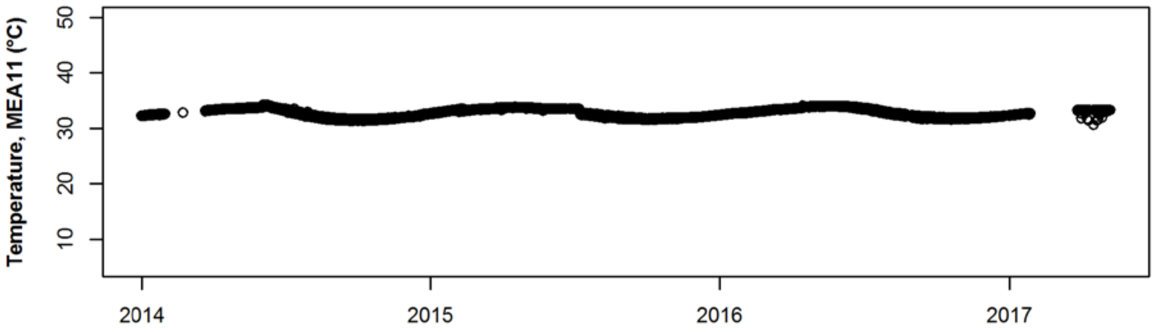

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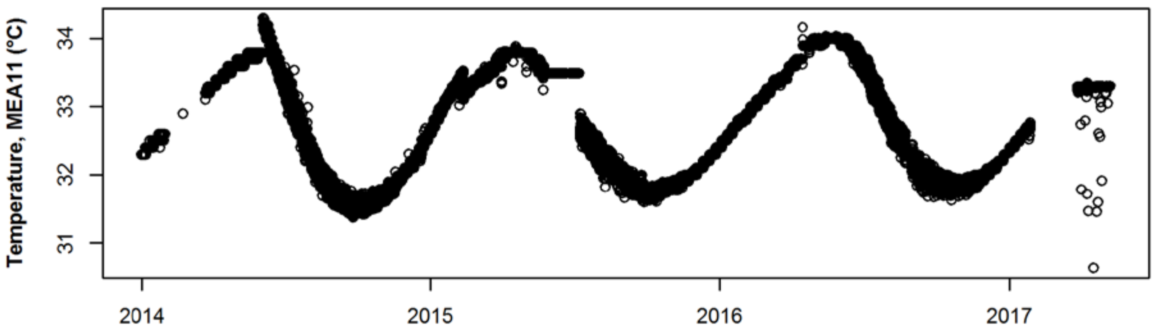
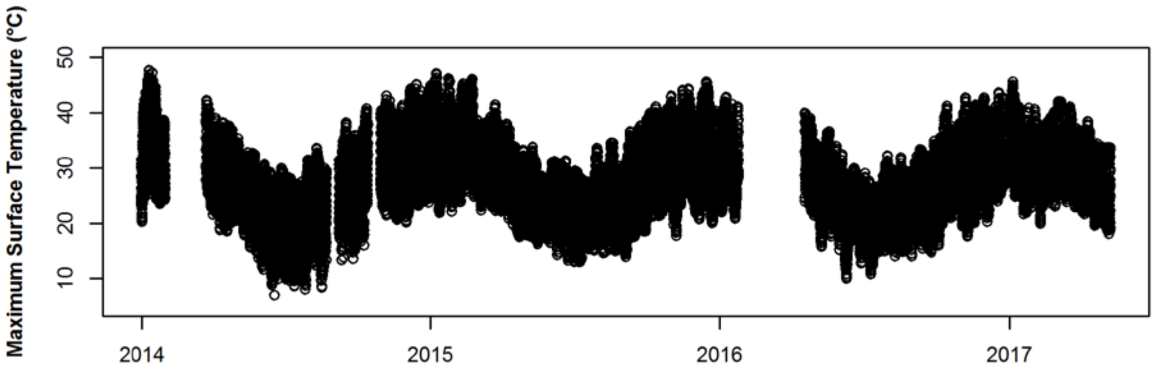


Figure 5: Logged temperatures at (a) the surface (hourly maxima) and (b and c) temperature probe MEA11 (5 m depth). The lower two figures are the same data; Figure b is on the same scale as the surface temperature plot, while the Figure c has a truncated y axis in order to highlight the sinusoidal curve.

(a)



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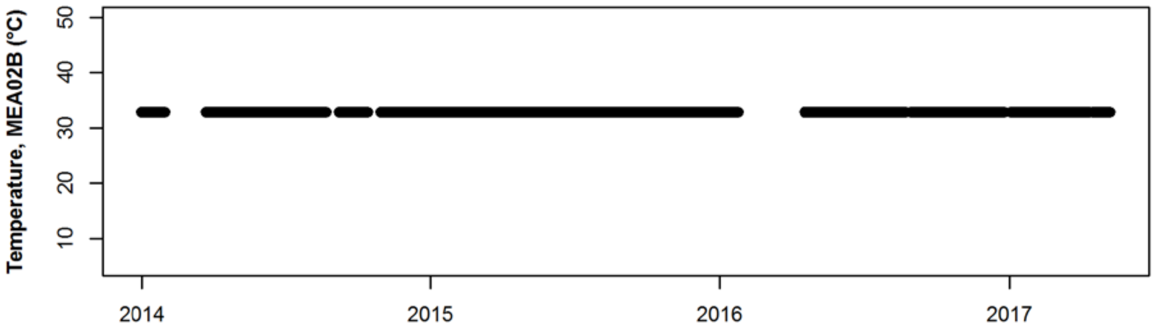

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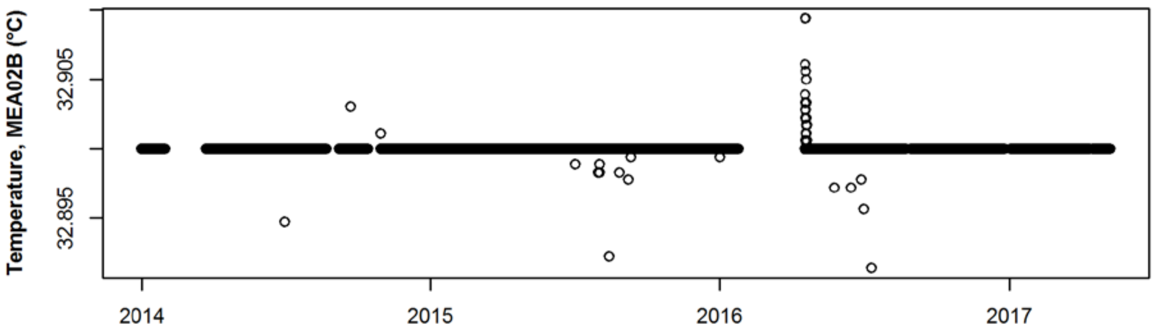
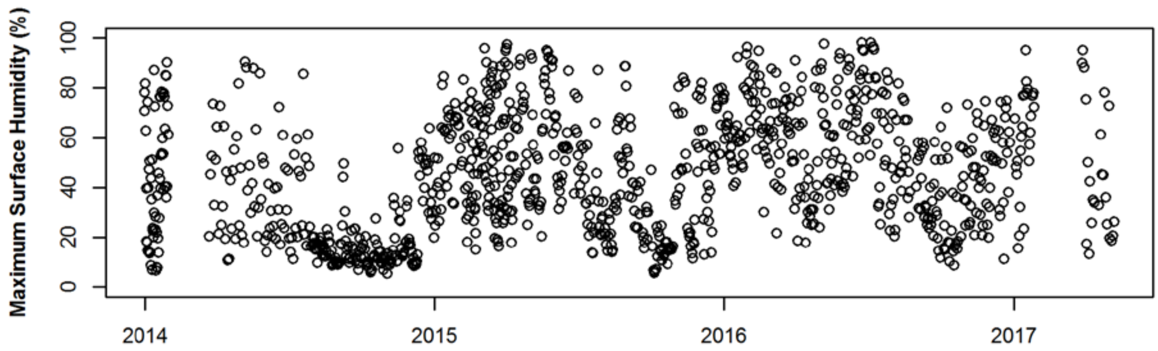
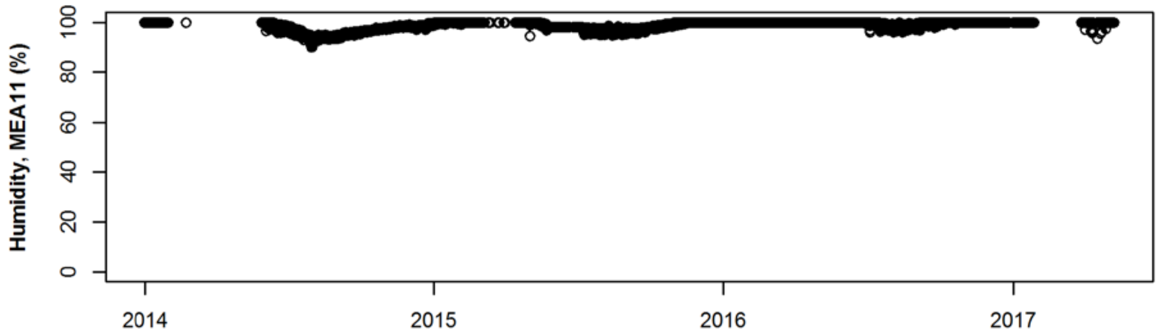


Figure 6: Logged temperatures at (a) the surface (hourly maxima) and (b and c) temperature probe MEA02B (22 m depth). The lower two figures are the same data; Figure b is on the same scale as the surface temperature plot to allow comparison, while Figure c has a truncated y axis in order to highlight any potential sinusoidal curve.

(a)



(b)



(c)

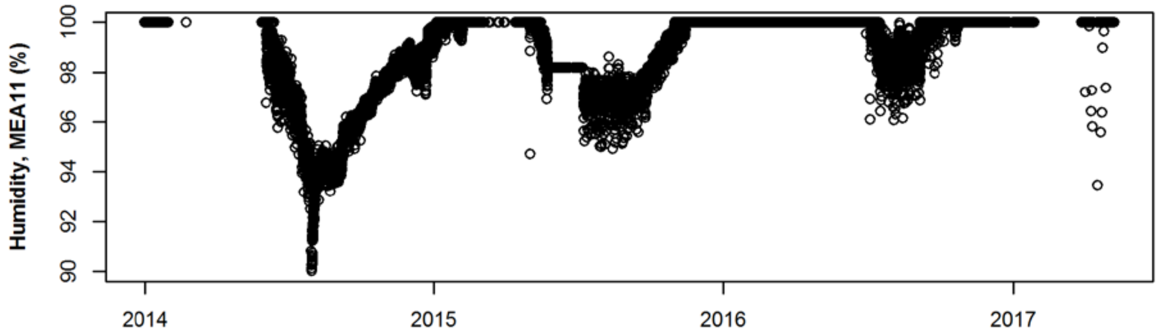
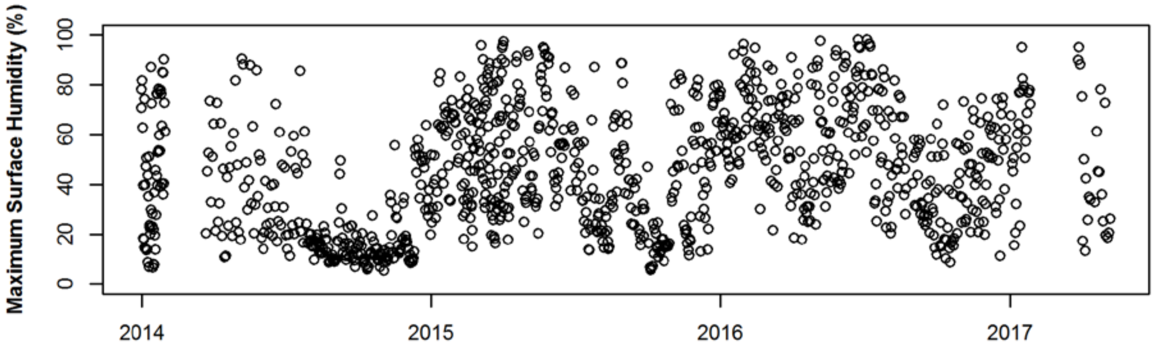


Figure 7: Logged humidity at (a) the surface (hourly maxima) and (b and c) humidity probe MEA11 (5 m depth). The lower two figures are the same data; Figure b is on the same scale as the surface temperature plot to allow comparison, while Figure c has a truncated y axis in order to highlight the sinusoidal curve. Points in the surface humidity plot were reduced to a daily point to improve clarity.

(a)



(b)

(c)

Figure 8: Logged humidity at (a) the surface (hourly maxima) and (b and c) humidity probe MEA02B (22 m depth). The lower two figures are the same data; Figure b is on the same scale as the surface temperature plot to allow comparison, while Figure C has a truncated y axis in order to highlight any potential sinusoidal curve. Points in the surface humidity plot were reduced to a daily point to improve clarity.

4 Conclusions

Data analysed covered the period from 2014 to 2017. Pre 2014 data is currently excluded primarily due to the interaction between the temperature sensor and the humidity sensor's heater in each individual probe; a problem that was rectified in late 2013. This truncation of temporal data has excluded any categorical pre/post impact comparisons, and hence analyses focused primarily on spatial comparisons. Changes in climate variables from 2014 to 2017 were also assessed.

Conclusions based on these data are:

- Proximity to the Mesa A pit edge did not influence mean subterranean temperatures or humidities.
- With increased proximity to Mesa A pit edge, humidity became more variable, and more strongly resembled a sinusoidal pattern of temporal change. Increasing strength of sinusoidal curves could potentially indicate an increased connectivity with surface climate. However, some of the highest values for variation in humidity were observed approximately 100 m from the pit edge and these values were not explained by probe depth. Variation observed is also within the error margins of probes at high humidity (±5% RH at 100% RH).
- In comparison to other sites (Mesa B and Mesa K), Mesa A did not demonstrate significantly different variation in humidity values or temperature values, or their fit to sinusoidal curves.
- Subterranean temperature and humidity at Mesa A have not changed significantly over time since January 2014. This lack of change is reflected in stable surface temperatures and humidity over the same period.

These four conclusions lead to the suggestion that activity at the Mesa A mine site has had little discernible influence on subterranean climate.

A remaining question however, is whether the current data set can be relied upon to derive reliable conclusions. The current analyses have attempted to diminish the influence of step changes by focusing on the average or overall response of probes, rather than analysing patterns in probes individually. The frequency and magnitude of step changes associated with equipment maintenance are expected to be randomly distributed across the probes, and therefore, on average any other significant patterns in the overall data set should be demonstrable with reasonable statistical power.

Data with step changes and other unexplained variation is a source of intrinsic error. The principal consequence of this error is higher variation leading to lower statistical power and lower ability to detect statistically significant differences such as the effect of an environmental impact. Any increase in data quality is usually aimed at increasing the likelihood of detecting an impact if one had occurred. Clearly, less noisy data sets have less error around statistical estimates and are hence more powerful (that is, more likely to detect an impact). The current data are thought to be reasonably powerful, as it has demonstrated the expected association between sinusoidal variation in temperature and probe depth.

Post 2014 data could be improved by adjusting data where known probe changes occurred. Unfortunately there is no knowledge of the actual values (for example, no record of true values at the time of probe change) to improve calibration. Therefore arbitrary rules regarding the adjustments would need to be established. For example, the initial data could be considered the baseline, and all consequent values are adjusted accordingly, where equipment changes are noted. This would also be relatively labour intensive as there is no simple way to automate the process, with data assessed visually and adjustments made individually to each step change within each probe data set. A convenient and informative location to begin data correction is the area containing the stations spatially associated with the latest clearing (2013, MEA06 and MEA07).

Cigna (2002) highlights that measuring humidity around the point of saturation is extremely challenging from a technical perspective no matter what equipment is deployed. This presents a particular challenge when considering the habitats of troglofauna where dependency upon a saturated environment may prove crucial.

The literature frequently suggests that the stable temperature found within subterranean habitats is similar to that of the average surface temperature. However, in the current study, average surface temperature was 27.3°C, while mean temperatures which were logged in subterranean habitats were generally 30°C to 35°C. Such contrasts in information suggests that more data on local subterranean systems is required, and that broad generalisations derived from other regions do not necessarily apply in the Pilbara subterranean environment.

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Appendix A: Maps of Sites and Probe Locations

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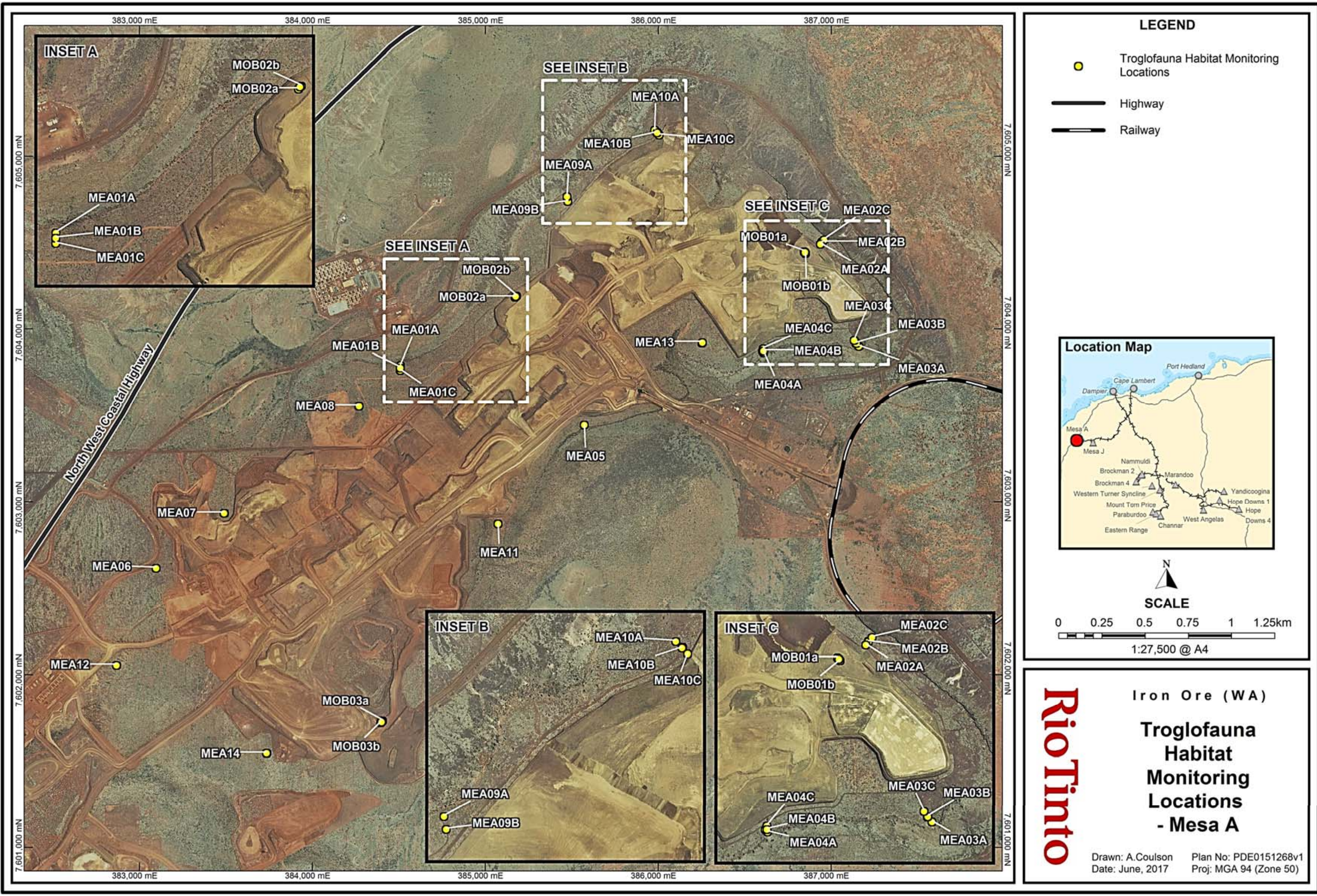
LEGEND
Troglofauna Habitat Monitoring Locations
Highway
Railway
Location Map
Port Hedland
Cape Lambert
Dampier
Mesa A
Mesa J
Nammuldi
Brockman 2
Brockman 4
Marandoo
Western Turner Syncline
Mount Tom Price
Paraburdoo
Channar
Eastern Range
West Angelas
Yandicoogina
Hope Downs 1
Hope Downs 4
N
SCALE
0 0.25 0.5 0.75 1 1.25km
1:27,500 @ A4
Rio Tinto
Iron Ore (WA)
Troglofauna Habitat Monitoring Locations - Mesa A
Drawn: A.Coulson
Date: June, 2017
Plan No: PDE0151268v1
Proj: MGA 94 (Zone 50)
383,000 mE
384,000 mE
385,000 mE
386,000 mE
387,000 mE
7,605,000 mN
7,604,000 mN
7,603,000 mN
7,602,000 mN
7,601,000 mN
North West Coastal Highway
SEE INSET A
SEE INSET B
SEE INSET C
INSET A
INSET B
INSET C
MOB02b
MOB02a
MEA01A
MEA01B
MEA01C
MEA10A
MEA10B
MEA10C
MEA09A
MEA09B
MOB01a
MOB01b
MEA02A
MEA02B
MEA02C
MEA03A
MEA03B
MEA03C
MEA04A
MEA04B
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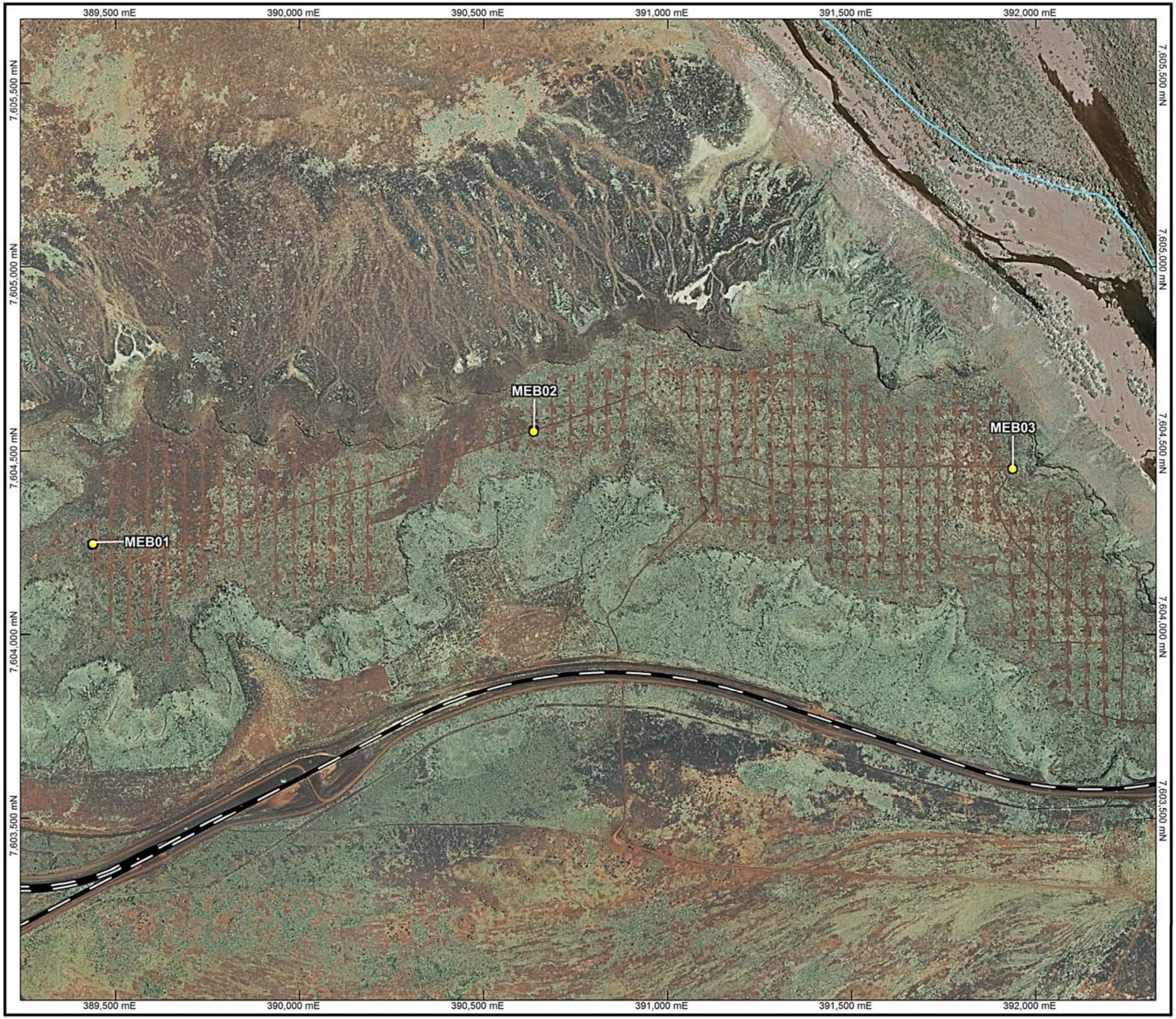
MEA14
MOB03a
MOB03b



LEGEND

- Troglofauna Habitat Monitoring Locations
- Railway
- Major Creek/River

N

SCALE

0 200 400 600m

1:15,000 @ A4

RioTinto

Iron Ore (WA)

Troglofauna Habitat Monitoring Locations - Mesa B

Drawn: A.Coulson
Date: June, 2017

Plan No: PDE0151268v1
Proj: MGA 94 (Zone 50)

LEGEND

- Troglofauna Habitat Monitoring Locations
- Railway
- Major Creek/River

N

SCALE

0 100 200 300 400 500m

1:12,500 @ A4

Rio Tinto

Iron Ore (WA)

Troglofauna Habitat Monitoring Locations - Mesa K

Drawn: A.Coulson
Date: June, 2017
Plan No: PDE0151268v1
Proj: MGA 94 (Zone 50)

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Appendix B: Summary of Probe Depths and Locations

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Table B1: Summary of probe depth and locations.

Location	Site/station	Hole	Distance to pit face (m)	Distance to escarpment (m)	Comments
Mesa A	MEA1	MEA01A	237	22	No obvious pit face from imagery. Localised clearing but not benched
		MEA01B	228	33	No obvious pit face from imagery. Localised clearing but not benched
		MEA01C	215	47	No obvious pit face from imagery. Localised clearing but not benched
	MEA2	MEA02A	15	46	Escarpment access ramp backfilled to pit crest directly adjacent to monitoring station
		MEA02B	29	33	Escarpment access ramp backfilled to pit crest directly adjacent to monitoring station
		MEA02C	48	14	Escarpment access ramp backfilled to pit crest directly adjacent to monitoring station
	MEA3	MEA03A	145	20	
		MEA03B	125	42	
		MEA03C	105	47	
	MEA4	MEA04A	38	12	
		MEA04B	31	21	
		MEA04C	20	31	
	MEA5	MEA05	43	15	
	MEA6	MEA06	127	NA	No Escarpment. No obvious pit bench to measure to. Localised clearing but not mined
	MEA7	MEA07	53	586	No obvious escarpment from imagery
	MEA8	MEA08	272	232	No obvious pit face from imagery. Localised clearing but not benched
	MEA9	MEA09A	70	14	Pit face has been backfilled to pit crest with LG/Waste material
		MEA09B	49	41	Pit face has been backfilled to pit crest with LG/Waste material
	MEA10	MEA10A	41	31	Partial backfill at pit face
		MEA10B	21	49	Partial backfill at pit face

Location	Site/station	Hole	Distance to pit face (m)	Distance to escarpment (m)	Comments
Mesa A		MEA10C	5	66	Partial backfill at pit face
	MEA11	MEA11	41	96	No obvious escarpment. Undulating but not a drop off
	MEA12	MEA12	407	NA	No Escarpment. No obvious pit bench to measure to. Localised clearing but not mined
	MEA13	MEA13	119	106	
	MEA14	MEA14	142	NA	No Escarpment
Mesa B	MEB1	MEB01A	NA	110	No mining
	MEB2	MEB02A	NA	111	No mining
	MEB3	MEB03A	NA	48	No mining
Mesa K	MEK1	MEK01	47	221	
	MEK2	MEK02	28	211	
	MEK3	MEK03	60	NA	
	MEK4	MEK04	56	NA	
	MEK5	MEK05	78	NA	
	MEK6	MEK06	NA	31	
	MEK7	MEK07	480	390	
	MEK8	MEK08	210	610	
	MEK9	MEK09	220	630	No climate data
	MEK10	MEK10	163	35	

Appendix C: Complete Monitoring Data, Plotted by Probe

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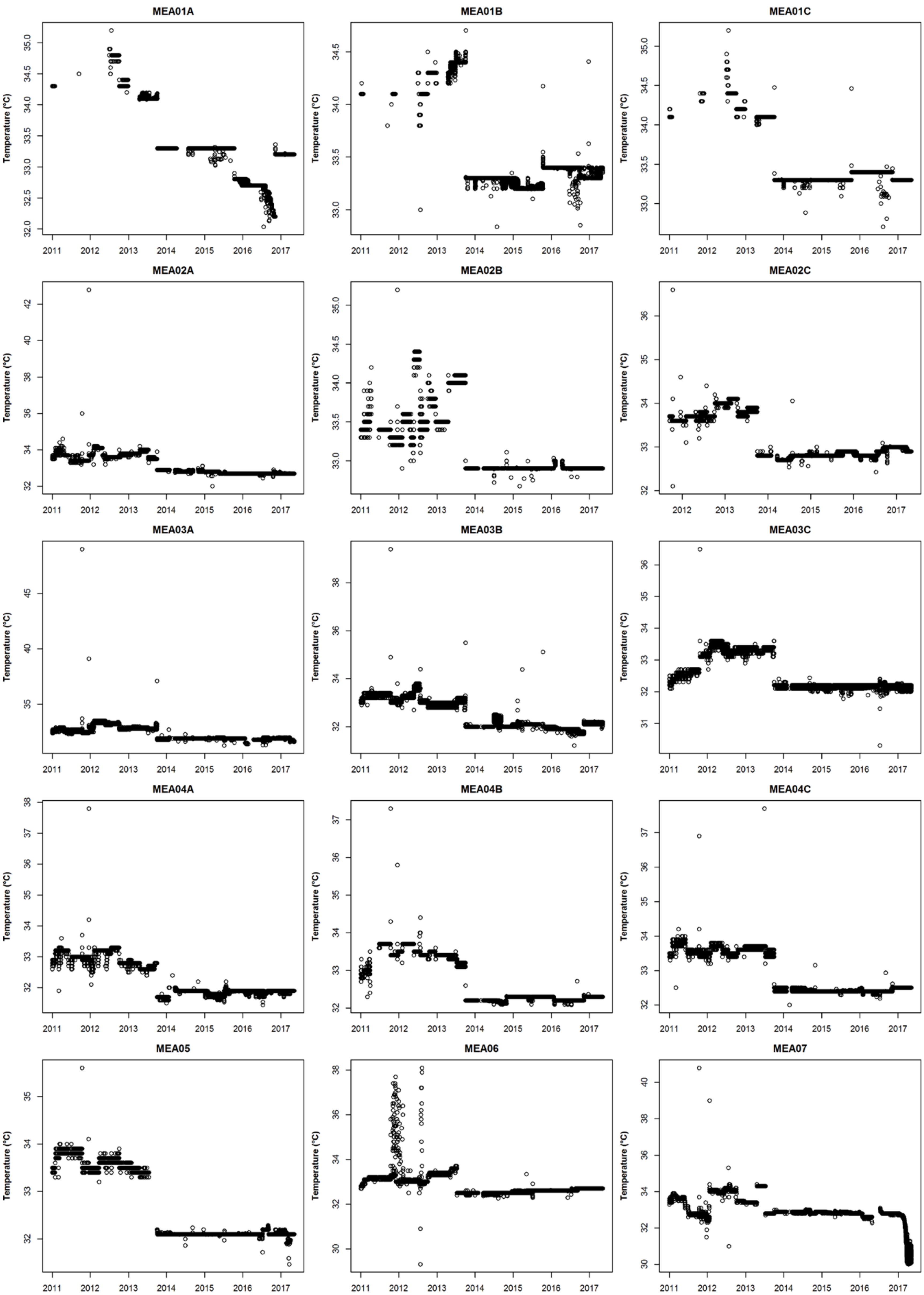

Figure C1.1: Plotted temperature data from each subterranean probe, 2011– 2017.

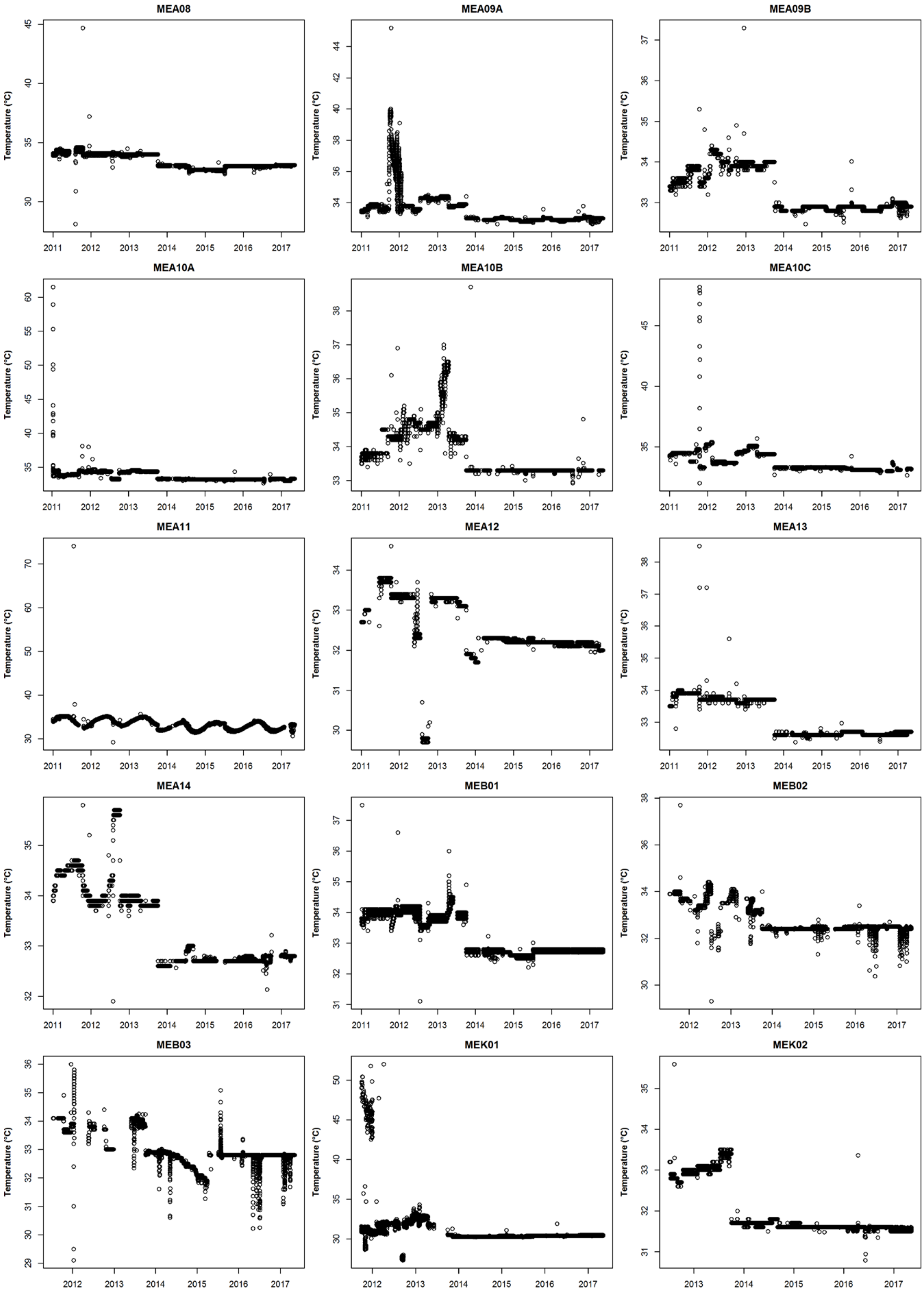

Figure C1.2: Plotted temperature data from each subterranean probe, 2011– 2017.

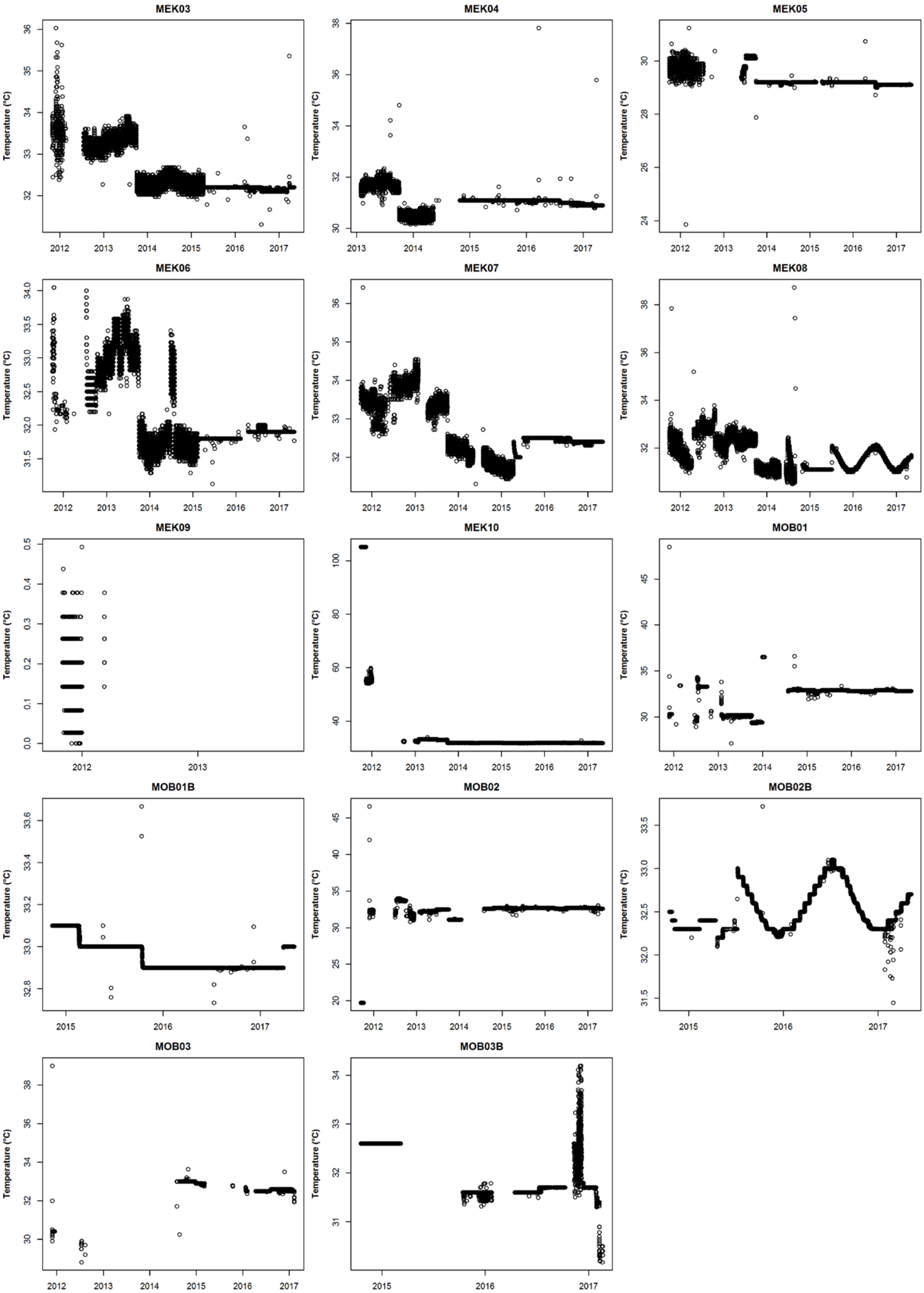

Figure C1.3: Plotted temperature data from each subterranean probe, 2011– 2017.

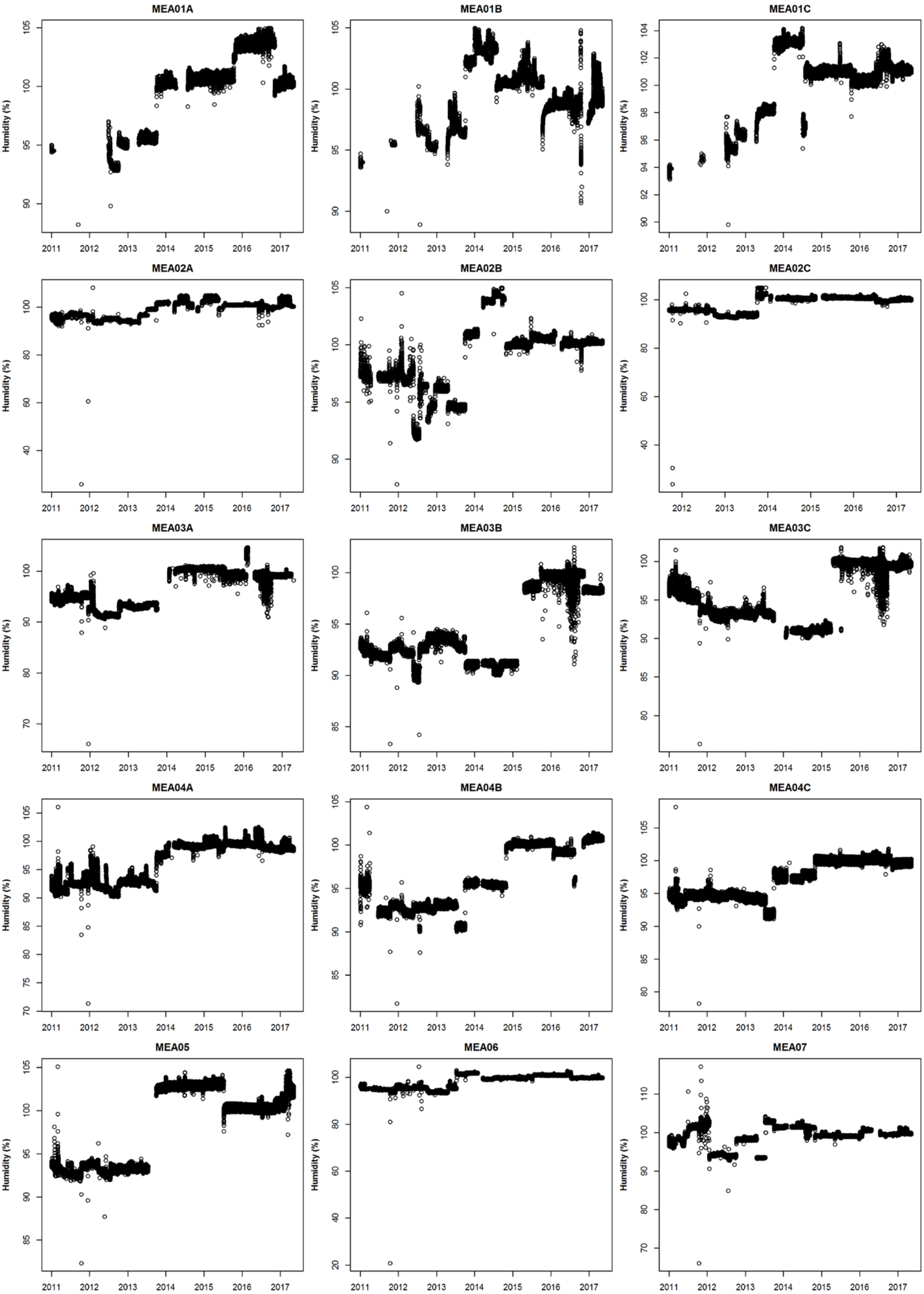

Figure C2.1: Plotted relative humidity data from each subterranean probe, 2011– 2017.

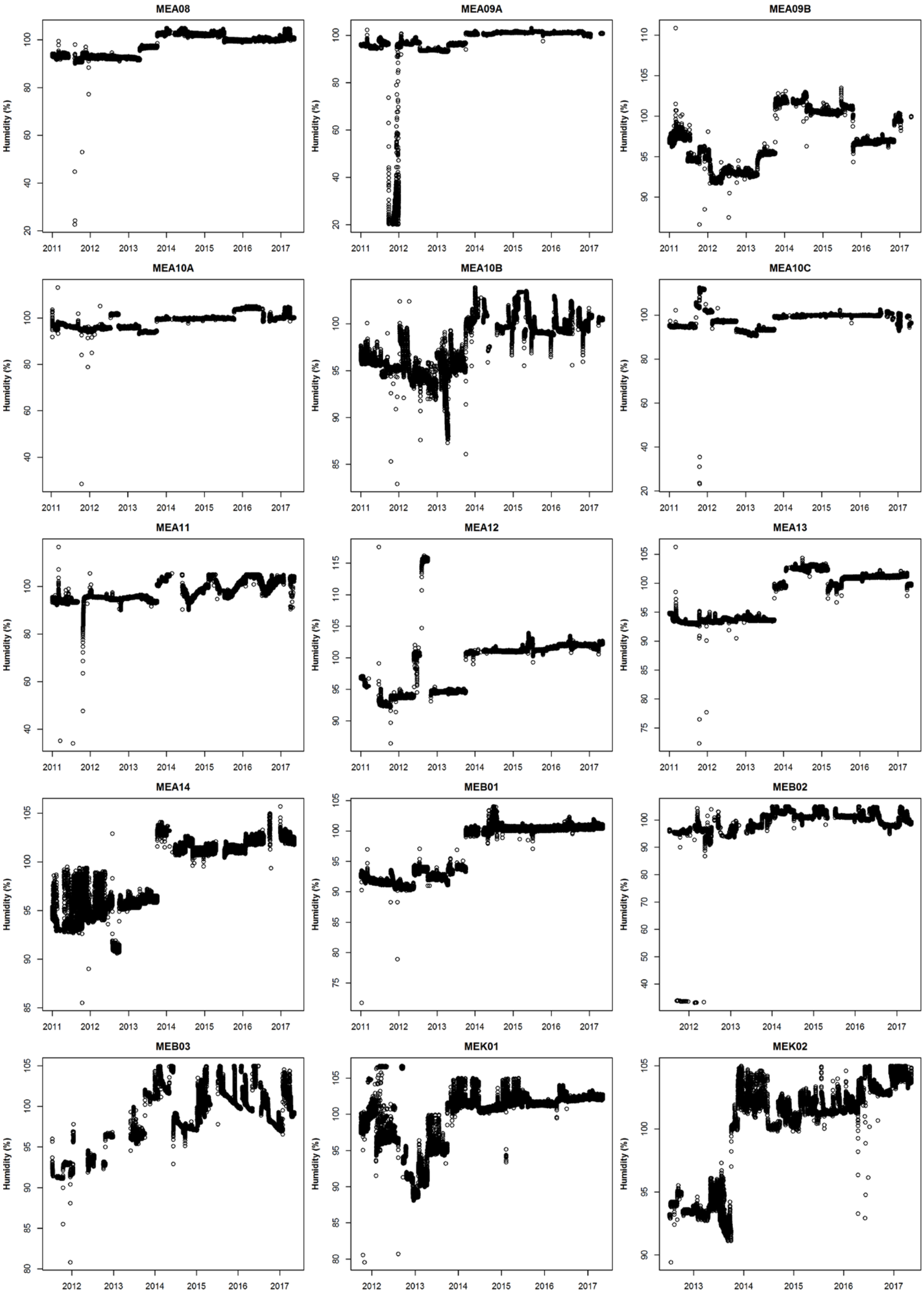

Figure C2.2: Plotted relative humidity data from each subterranean probe, 2011– 2017.

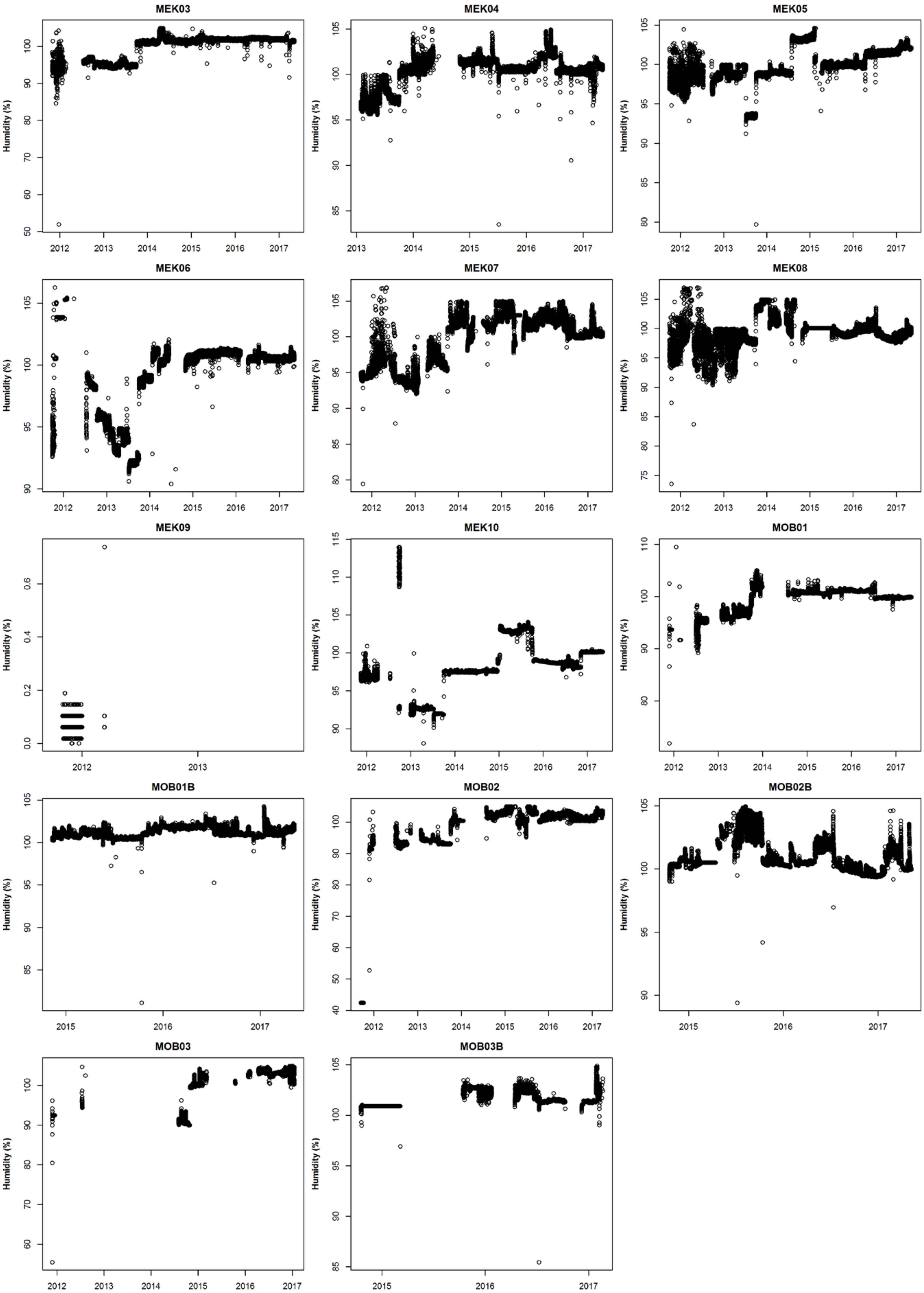

Figure C2.3: Plotted relative humidity data from each subterranean probe, 2011– 2017.

Appendix D: Truncated Monitoring Data (2014 to 2017), Plotted by Probe, with Sinusoidal Curves

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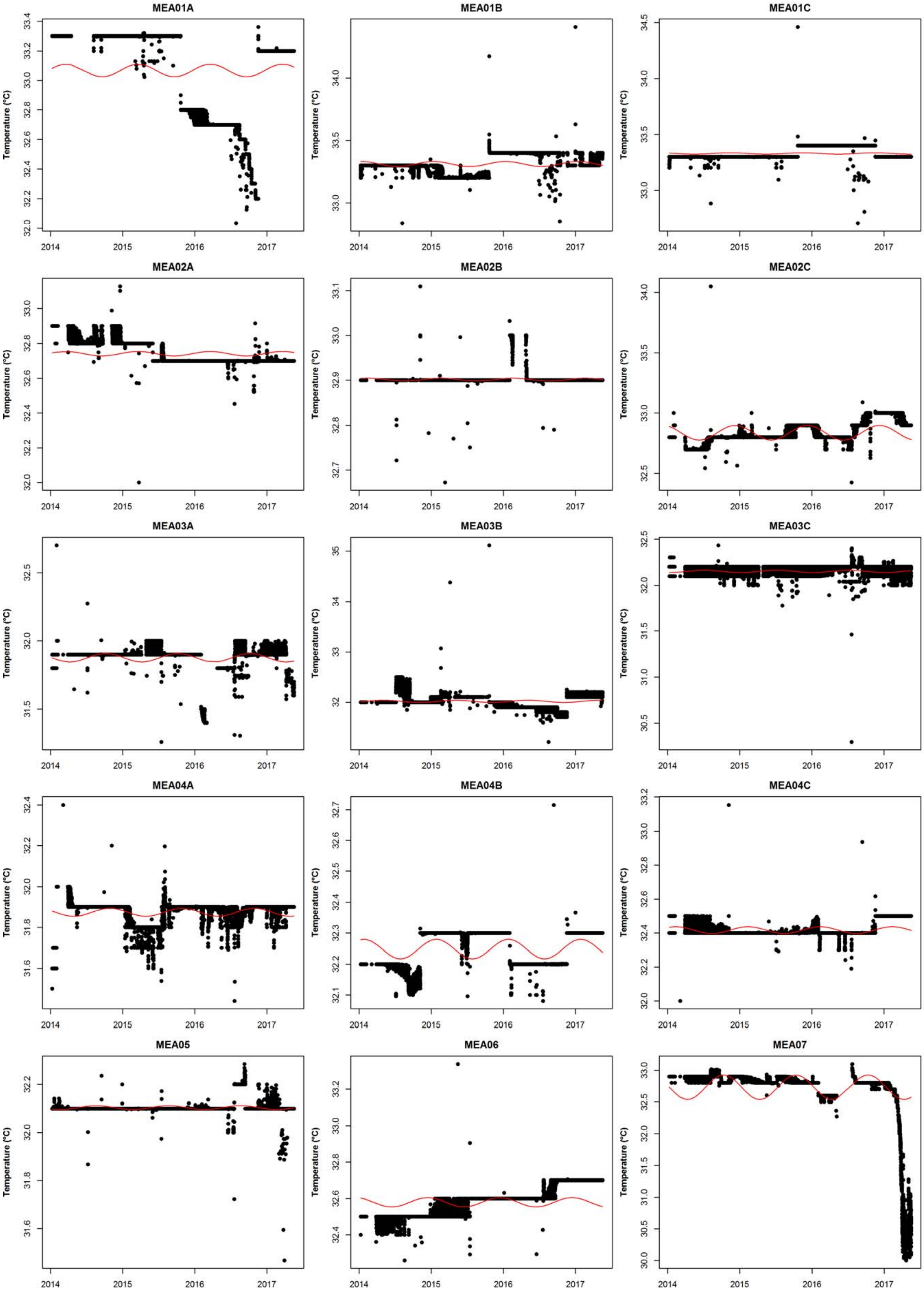

Figure D1.1: Plotted temperature data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.

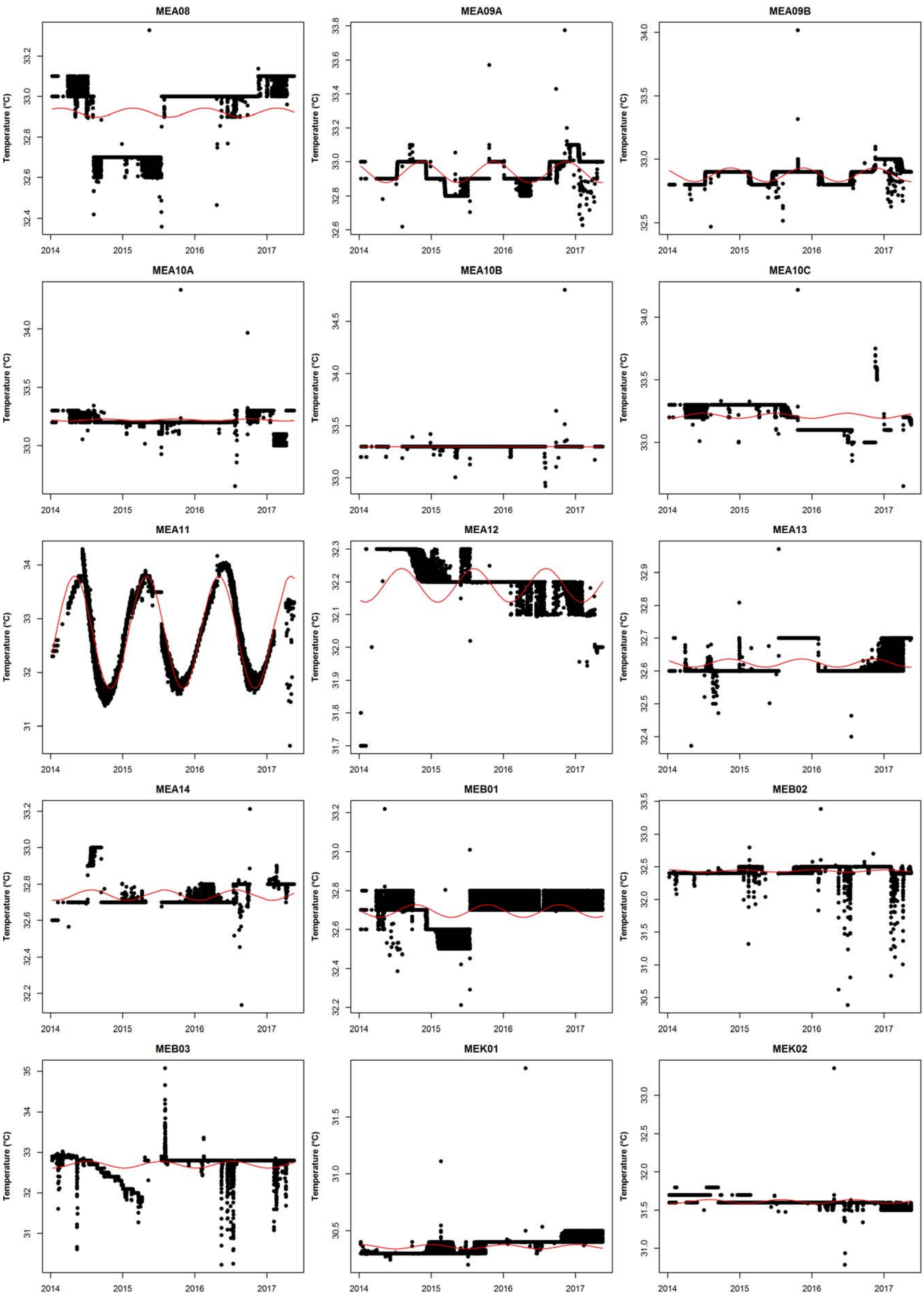

Figure D1.2: Plotted temperature data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.

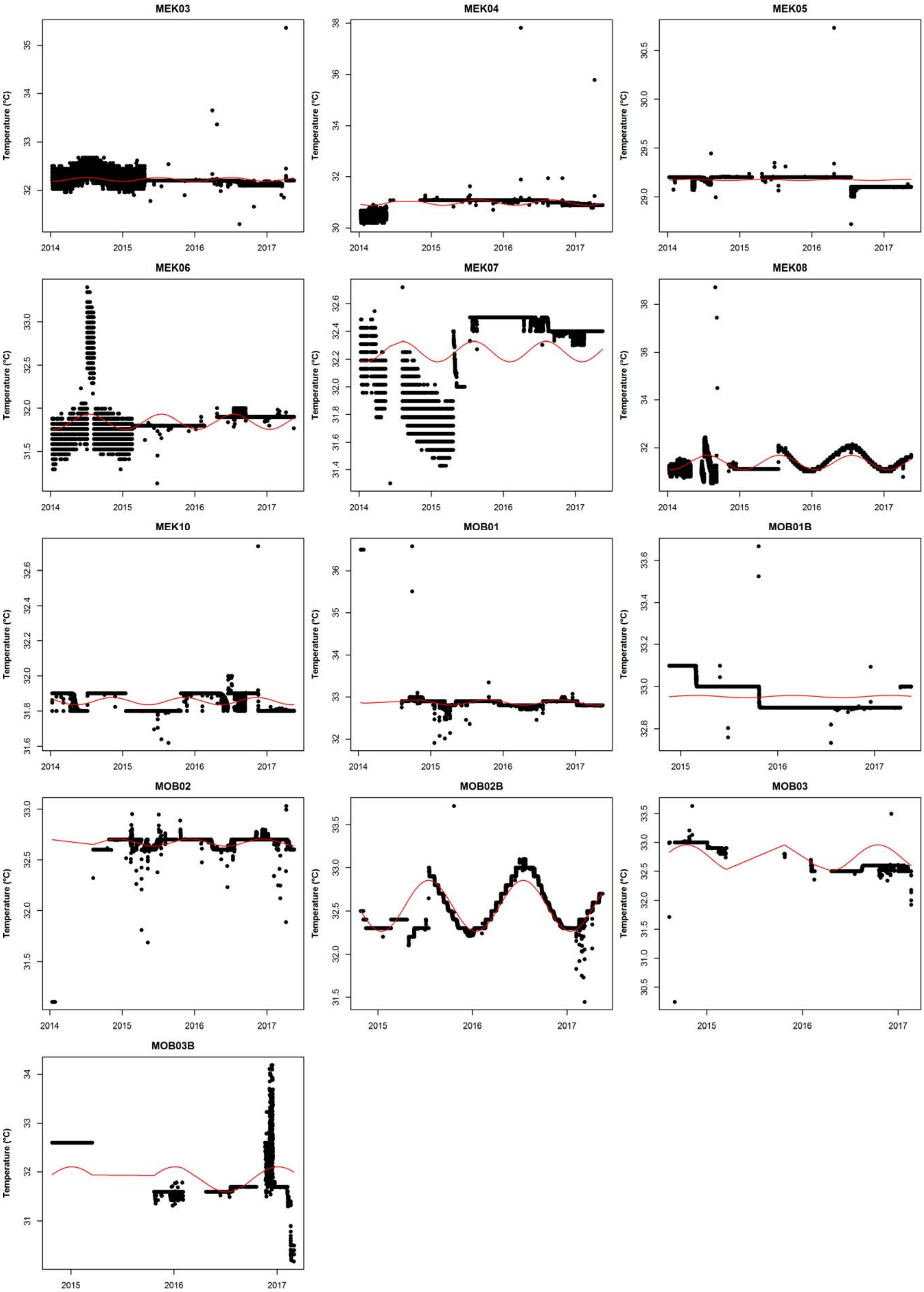

Figure D1.3: Plotted temperature data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.

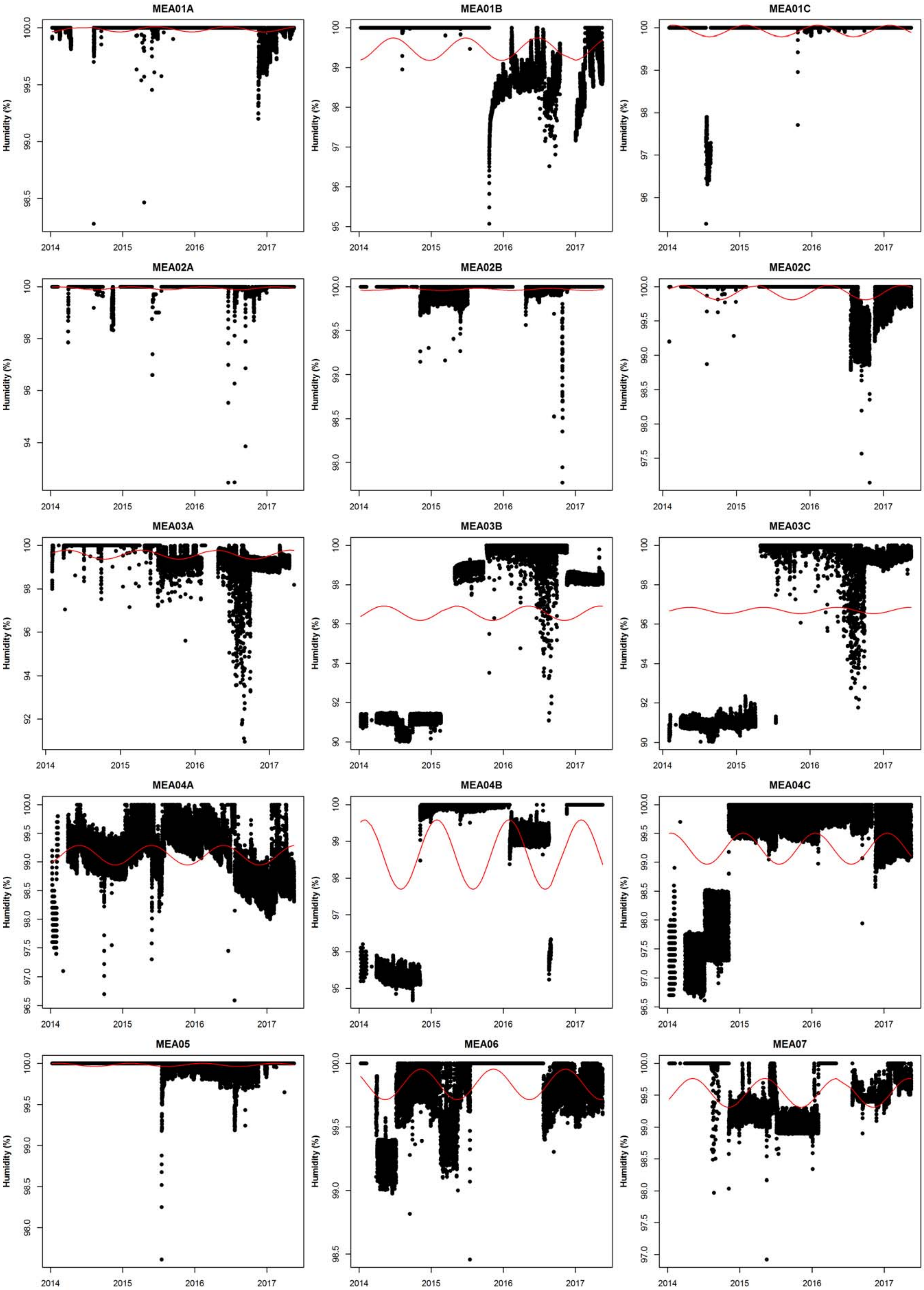

Figure D2.1: Plotted relative humidity data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.

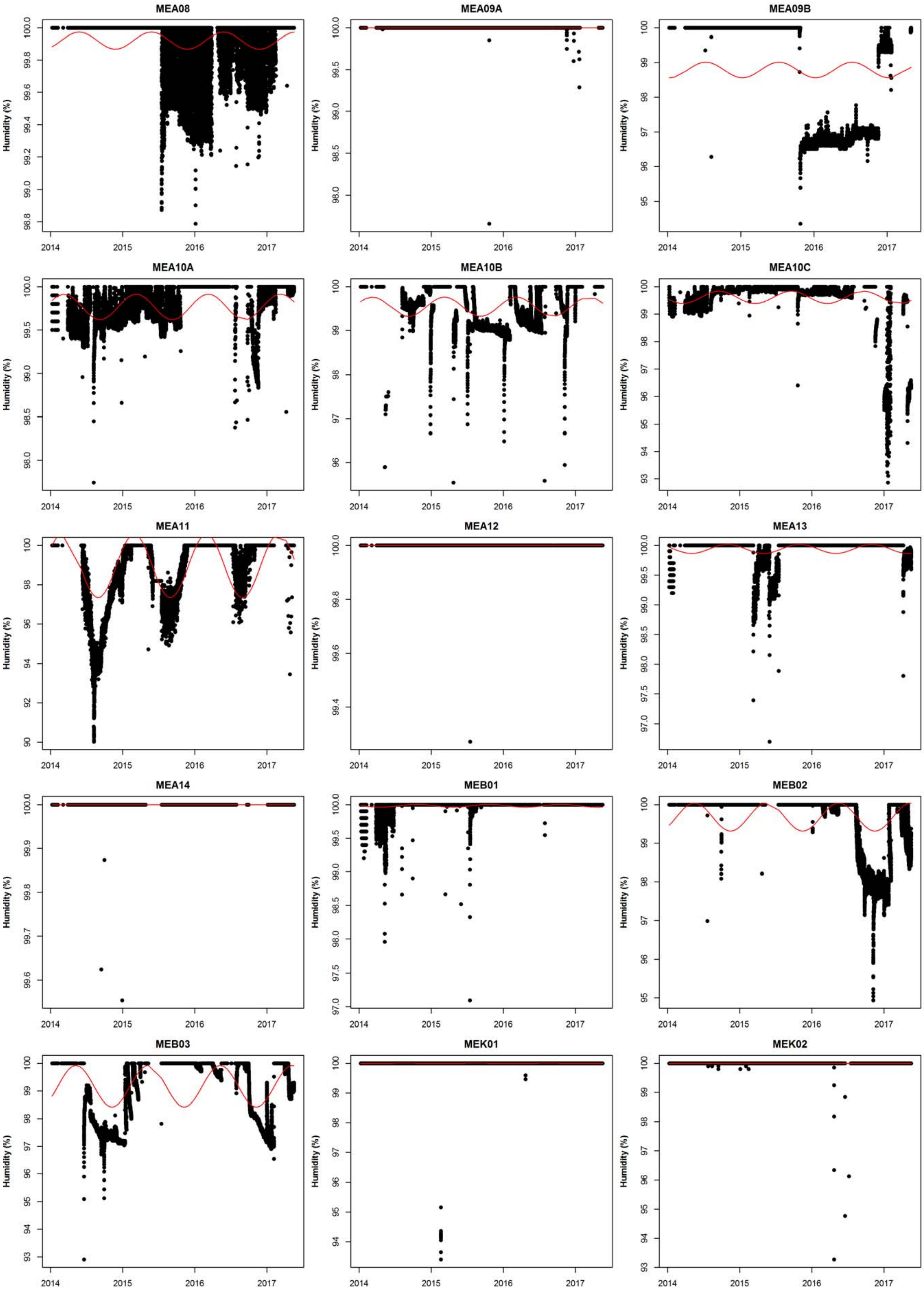

Figure D2.2: Plotted relative humidity data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.

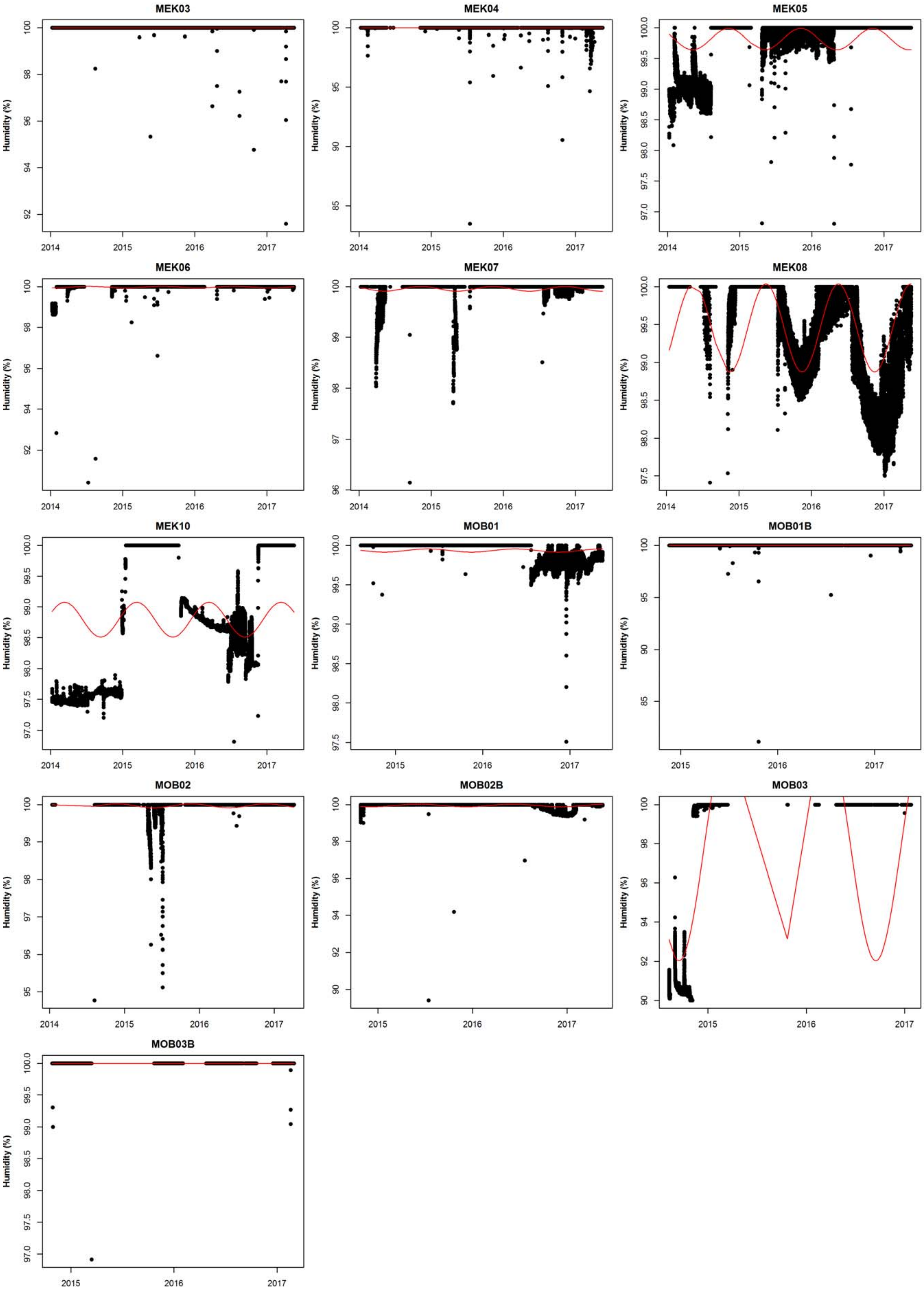

Figure D2.3: Plotted relative humidity data from each subterranean probe, 2014 – 2017. The red line represents the best fitted sinusoidal curve based on an annual cycle.