Guide to Soil Moisture and Soil Temperature Data Collected in Owens Valley, CA during March and April 2006 as part of the Terrain-Induced Rotor Experiment

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1 Introduction

Thirty soil moisture and temperature sensors were installed at 23 locations in Owens Valley, CA as part of the Terrain-Induced Rotor Experiment (T-REX) which took place in March and April, 2006. Site locations were chosen based on a number of considerations including accessibility, elevation, and representation of the surrounding area. Some sensors were co-located with other instruments including University of Utah HOBOs, University of Leeds flux towers, DRI towers, and Inyo County long-term soil moisture monitoring stations. Sites were chosen along several transects roughly perpendicular to the valley axis so that patterns in soil moisture could be identified (e.g. higher or lower soil moisture on the valley side walls compared to the valley floor, or along-valley trends). T-REX observations were centered around Independence, so the main and central line of soil moisture sensors crossing the valley ran through Independence as well. All sensors were installed by the end of January, allowing at least a month for the sensors to settle into the soil before the start date of the T-REX field campaign on March 1, 2006.

Sites have been labeled S1 through S25 (S7 and S21 were never installed due to snow coverage.) Site locations in Owens Valley are shown in Fig. 1. Details such as latitude and longitude as well as site characteristics are given in the tables in the Appendix.

2 Data Files

There are two file formats available for download. Both formats contain the same four variables: date and time (mm/dd/yyyy 00:00:00), time in days (decimal days of 2006), soil moisture (VWC (m^3/m^3)), and soil temperature (°C). Two time variables are provided since each is convenient for different applications (e.g. plotting may be easier using decimal days). The first format is a simple text file (with the extension: .txt). File names are constructed as follows, for example: if the site name is S2, and the logger number is 1332, then the file name is: "S2Logger1332.txt". There was one logger per sensor, so if multiple sensors were placed at a site, their data can be accessed based on their corresponding logger number. For example, at S8 there were three sensors whose data can be individually accessed in the files: S8Logger1334.txt, S8Logger1339.txt, S8Logger1440.txt. The second format is specifically for Matlab and has the extension: .mat. To load a "MAT-file" into Matlab, simply type, "load" followed by the file name (e.g. "S2Logger1332.mat"). The four variables will load into the Matlab workspace. The variable "dates" contains the dates, "timedays" contains time in days of 2006, "qsoilVWC" contains soil moisture in VWC, and "tsoilC" contains soil temperature in degrees Celsius.

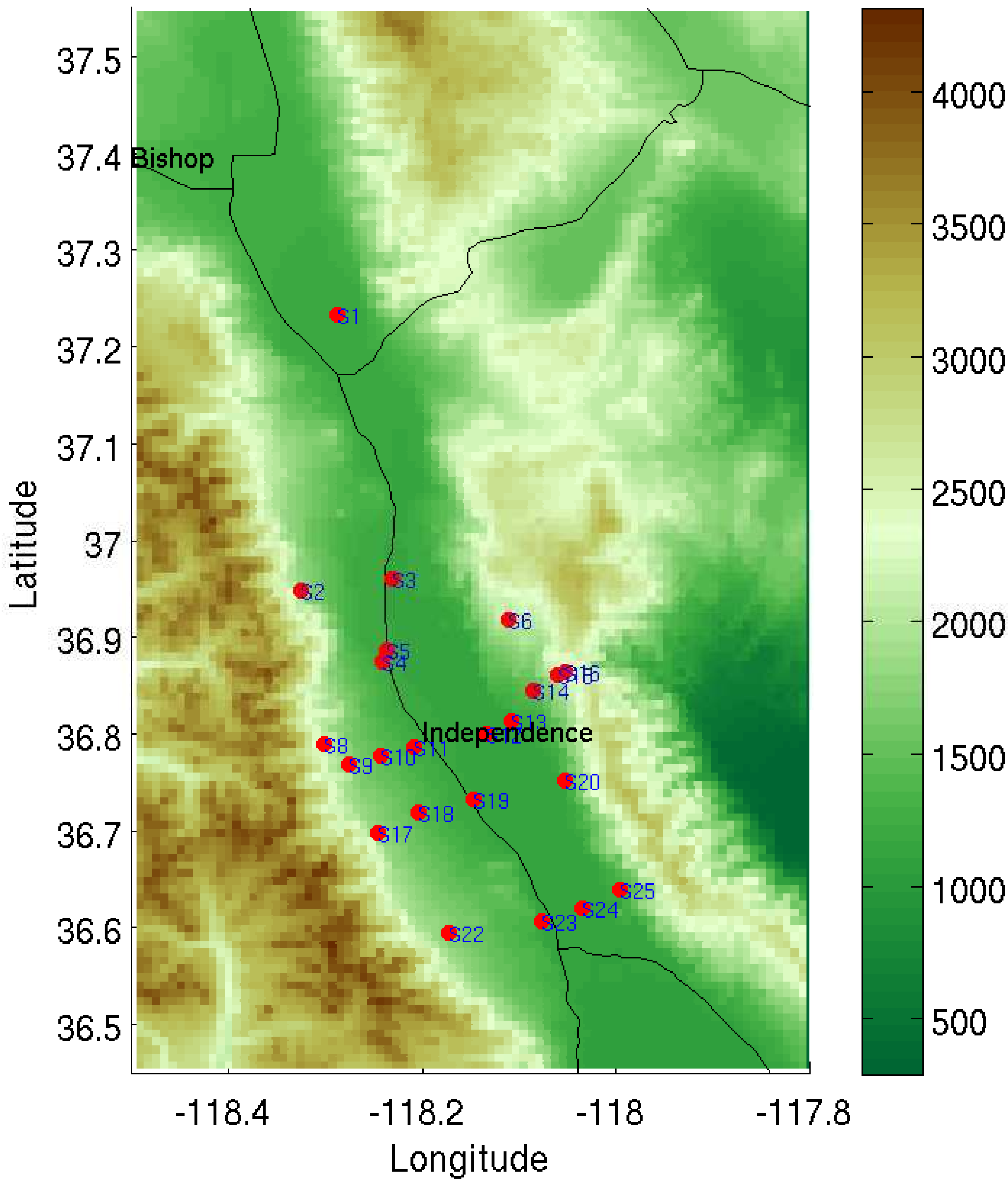


Figure 1: Soil moisture monitoring sites S1-S25 for T-REX in Owens Valley shown as red dots. Contour shading is terrain height in meters. Main roads are shown in black.

3 Soil Moisture Sensors: Decagon ECH2O Capacitance Probes

To measure soil moisture, we used the ECH2O EC-20 soil moisture probes manufactured by Decagon Devices. The ECH2O probes are capacitance-type sensors that measure the dielectric constant or permittivity of the soil at the depth at which they are buried. Since we are mostly interested in the surface layer of soil as input for atmospheric models, sensors were buried just 5 cm below the surface at every site. At a few sites additional sensors were installed at 20-50 cm depth (see Appendix for details).

Raw data from the sensors were recorded on Decagon EM50 data loggers. This raw data then was calibrated to represent volumetric water content (VWC), a standard measure of soil moisture. Volumetric water content can be defined as:

$$VWC = \frac{\text{Volume of Water}}{\text{Total Sample Volume}} \tag{1}$$

For convenience, the above fraction is often multiplied by 100 to yield percent volumetric water content, or %VWC. We will use this convention throughout this readme file.

3.1 Soil Moisture and Temperature Probe Installation

A hole about twice as deep as the probe insertion depth (about 10 cm deep for the majority of probes) was dug at each site. The soil moisture probe was inserted into the wall of the hole approximately perpendicular to the temperature probe at the same depth in an effort to allow maximum contact of undisturbed soil along the length of the soil moisture probe. The hole was then filled in using the original soil, and allowing the wires from both probes to protrude from the ground to be plugged into the data logger.

4 Calibration of EC-20 Probes

4.1 Procedure and Calculation

Decagon Devices provides a standard mineral soil calibration curve to convert raw data from the EC-20 probes to VWC. This standard curve was found to be inadequate for many of our sites, probably due to high salinity of the soil in Owens Valley. The standard curve gave negative values of VWC for several sites; to eliminate this problem, we performed our own soil calibration for each site individually by taking gravimetric soil moisture measurements on two dates for each of the sites. Our calibration procedure and calculation is based on the procedure and calculation outlined in Decagon's Application Note entitled, "Calibrating ECH2O Soil Moisture Probes" available at www.decagon.com.

Gravimetric water content can be defined as:

$$GWC = \frac{\text{Mass of Water}}{\text{Mass of Dry Soil}} \tag{2}$$

To calculate the gravimetric water content of the soil, at least two sample cores of soil were taken from each site. To convert our gravimetric measurements to %VWC, it was necessary to calculate the bulk density. Bulk density can be defined as:

$$\rho_B = \frac{\text{Total Mass of Sample (Soil and Water)}}{\text{Total Volume of Sample (Soil and Water)}} \tag{3}$$

Our sample core volumes were known, and each total sample was weighed. (The sample core volume was extracted at an average depth of 5 cm.) Sub-samples were then weighed and placed in an oven to bake for at least 12 hours. The dry sub-samples were then removed from the oven and weighed again. The mass of water was deduced by:

$$\text{Mass of Water} = \text{Mass of Sub-sample before baking} - \text{Mass of Sub-sample after baking} \tag{4}$$

Knowing the GWC and bulk density, we calculated %VWC for each site by:

$$\%VWC = GWC\frac{\rho_B}{\rho_w} \times 100 \tag{5}$$

where ρ_w is the density of water.

Thus we calculated GWC for each site on two dates, and then converted to %VWC using bulk density. For each site, at least two values of %VWC were calculated, (based on the two core samples taken), and combined to get an average %VWC for the site. We then extracted raw probe values for the dates and times corresponding to when the soil samples were taken. (So for example, the first set of soil samples for S2 were taken on March 31, 2006 at 8:30 AM and were found to have an average value of 15.2 %VWC with a raw probe reading of 703, giving us our first point on the graph relating raw probe values to %VWC. This was also done for the second set of soil samples, giving us our second point.) For each site, we then calculated a slope and intercept for the line between the two points which was considered to be the calibration “curve” for the site. (The raw data measured at the site is generally linearly proporational to VWC so this is a standard procedure.)

A few sites were lacking either a gravimetric measurement or a raw probe value at the time the soil sample was taken so that for these sites it was necessary to use a zero reading point to determine the slope and intercept of a calibration curve (e.g. a raw probe reading of 600 was considered to correspond to 0 %VWC.)

In addition to taking soil samples for gravimetric measurements at each site, we also used a TDR (Time Domain Reflectometry) instrument to measure soil moisture. We used two different TDRs, the TRIME, provided by NCAR, and the Hydrosense, provided by Inyo County Water District. Due to time constraints, we were only able to use one of these instruments at each site. It is important to note that TDRs often need to be individually calibrated themselves. We found that the TDR usually provided an estimate of soil moisture that was different from what we found using the gravimetric measurement method. In some cases the calibration based on the TDR was very close to the gravimetric calibration, but in other cases the calibration was not successful. The TDR calibration did however, often fall within the range of calibrations provided by Decagon Devices.

4.2 Temperature Effects

Freezing of the soil surrounding the probes causes spurious readings (extremely low readings) because the water present in the soil freezes and the probes are unable to measure frozen water. So if the temperature probe indicated that the soil temperature was below zero degrees Celcius, the soil moisture probe readings were neglected.

Decagon Devices indicated that the EC-20 probes may be sensitive to extreme heat, or strong temperature fluctuations ($\sim 30^\circ$) over the course of a day. This kind of temperature dependence has not been removed from the dataset in order to avoid averaging and perhaps distorting or smearing out other important patterns in the data. There is some natural fluctuation in soil moisture over the course of a day, so it is difficult to remove only the fluctuation due to the probe's sensitivity to temperature. (A temperature correction formula is provided by Decagon for standard ECH2O calibrations which are performed in a laboratory under controlled temperature conditions. Thus the temperature correction could not be used with our individual gravimetric calibrations based on field data.)

4.3 Error Estimates and Figures

Decagon estimates that the absolute error for the EC-20 using the standard mineral or sandy loam curve is + or - 4 %VWC. To get a rough estimate of the error in our gravimetric calibration, we looked at the differences between results for the two or more sub-samples weighed and baked for each site at two dates. Results for each of these sub-samples were then averaged over the number of sub-samples for each site. The difference between the %VWC calculated for each sub-sample at a given site varied from site to site from 0.06 %VWC for S1 to as much as 15.59 %VWC for S5 (which yielded an unsuccessful gravimetric calibration). Most of the sites fell in the range from 0.06 %VWC to about 5 %VWC difference between sub-sample results. Based on this observation, we place the error in our gravimetric calibration at approximately + or - 5 %VWC for the successful calibrations.

The following figures show results for four different calibration curves applied to data from the EC-20 soil moisture capacitace probe. Black markers indicate gravimetric measurements. Blue is the gravimetric calibration, green is the TDR (Time Domain Reflectometry) calibration, red is Decagon's standard mineral calibration (from the manual), and pink is Decagon's sandy loam calibration. (For one site, S3 we used an organic soil calibration provided by Decagon, rather than the Decagon's sandy loam calibration. This is indicated on the figure for S3.) Soil types for each site were determined via a simple "touch test" following the procedure set forth by East Dakota Water Development District (available online at: www.bigsiouxwaterfestival.org/tp28.htm). Results are given in a table in the appendix.

For most of the sites, the gravimetric calibration was used to calibrate the soil moisture data available from the T-REX data archive website (http://data.eol.ucar.edu/master_list/?project=T-REX). The calibration used for each sensor is indicated on the figures by a an asterisk in the legend. In two cases (S25 and S6), the gravimetric calibration yielded a slope opposite that of Decagon's standard mineral and sandy loam calibrations. This caused rain events to appear as periods of extreme drying instead of wetting, indicating that our gravimetric calibration was flawed for these sites. For S25, Decagon's sandy loam calibration was chosen because the mineral calibration produced negative soil moisture values (%VWC). For S6, Decagon's standard mineral calibration was chosen because it most closely approximated the range of the gravimetric measurements taken at the site. The soil at S6 was determined to be sandy clay by touch test, so it is debatable whether the sandy loam or standard mineral calibration is better for this site.

Note that days 30 through 125 represent the T-REX field campaign dates, though all days (if available) starting January 1, 2006 are shown in the plots. Temperature plots for each sensor are shown on the same page below each soil moisture plot.

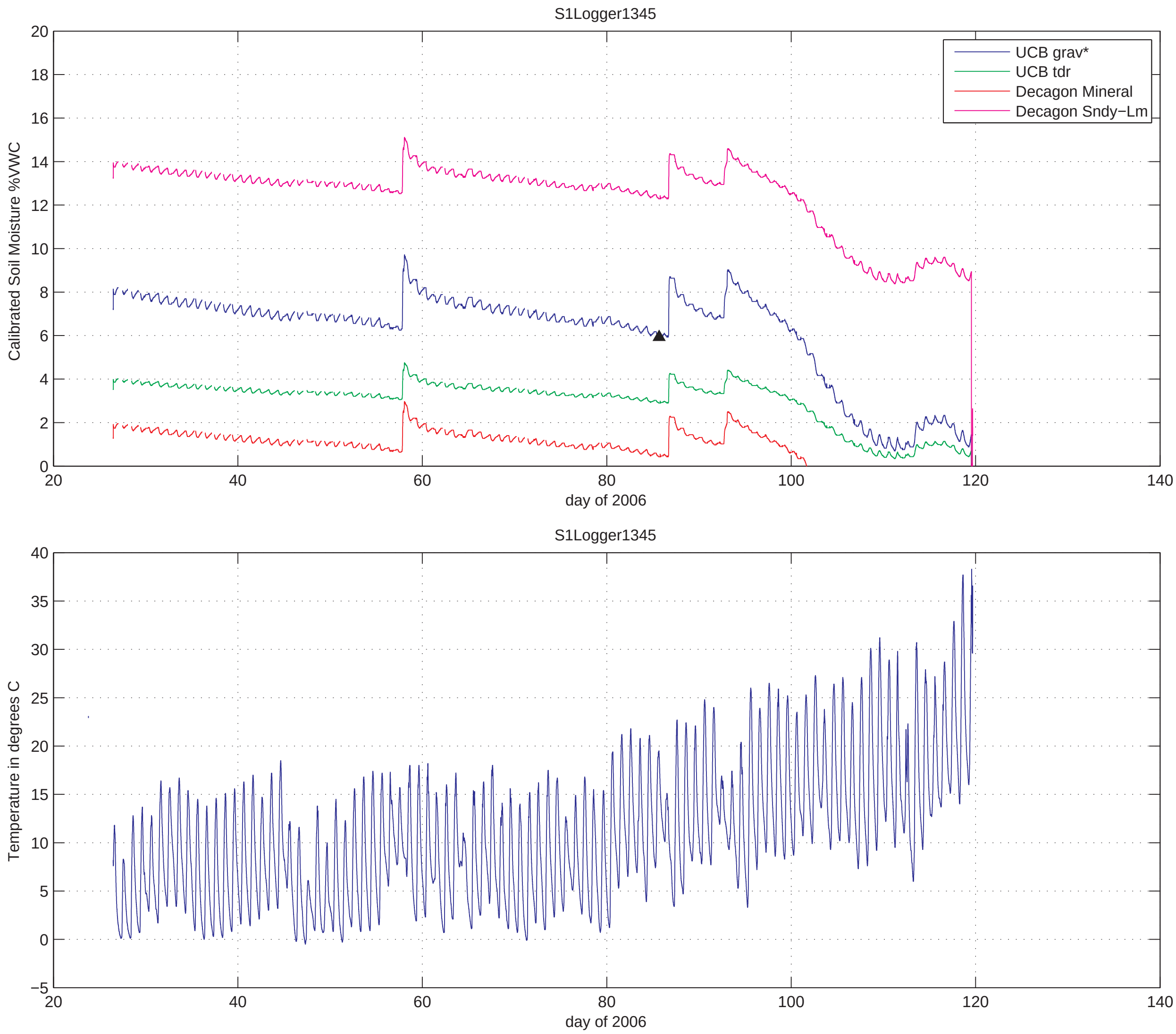
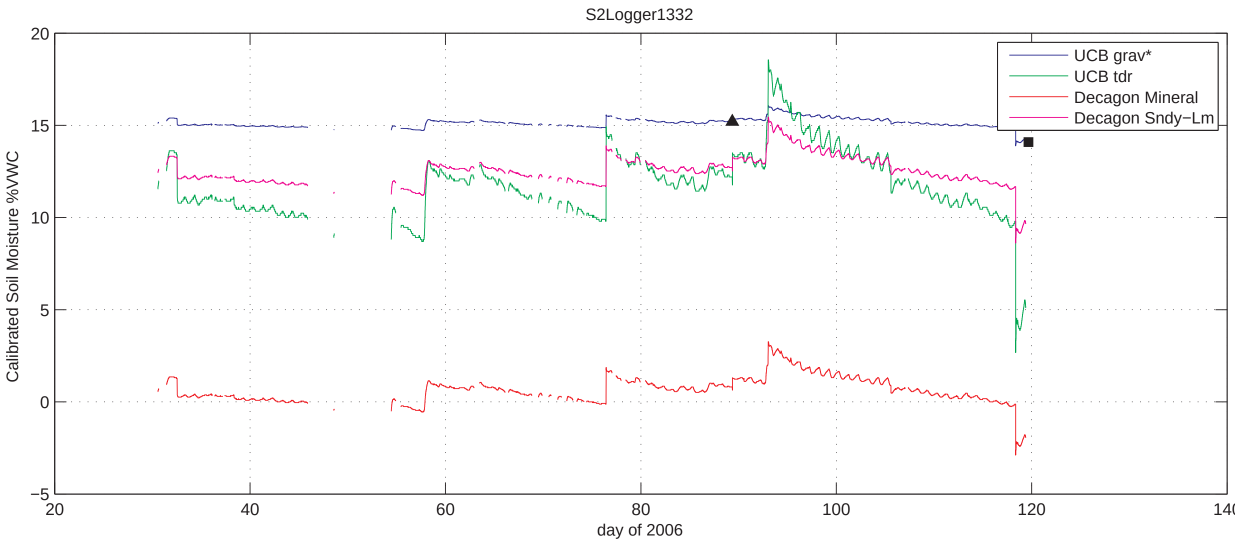


Figure 2: We only took one set of gravimetric measurements for this site.


S2Logger1332
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
20
15
10
5
0
−5
20
40
60
80
100
120
140

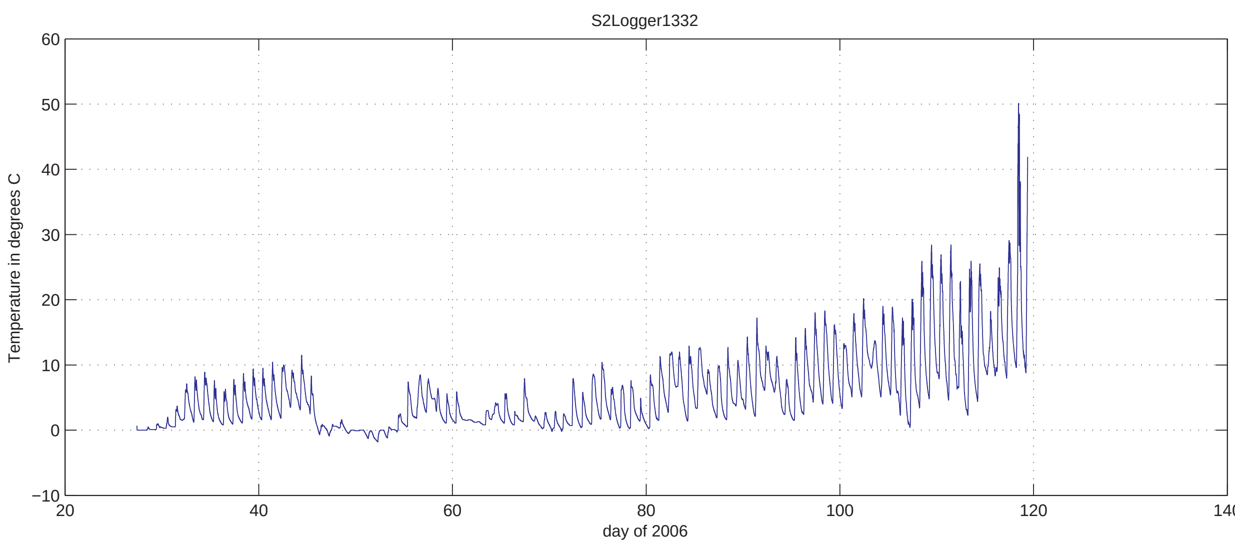

S2Logger1332
Temperature in degrees C
day of 2006
60
50
40
30
20
10
0
−10
20
40
60
80
100
120
140

Figure 3:

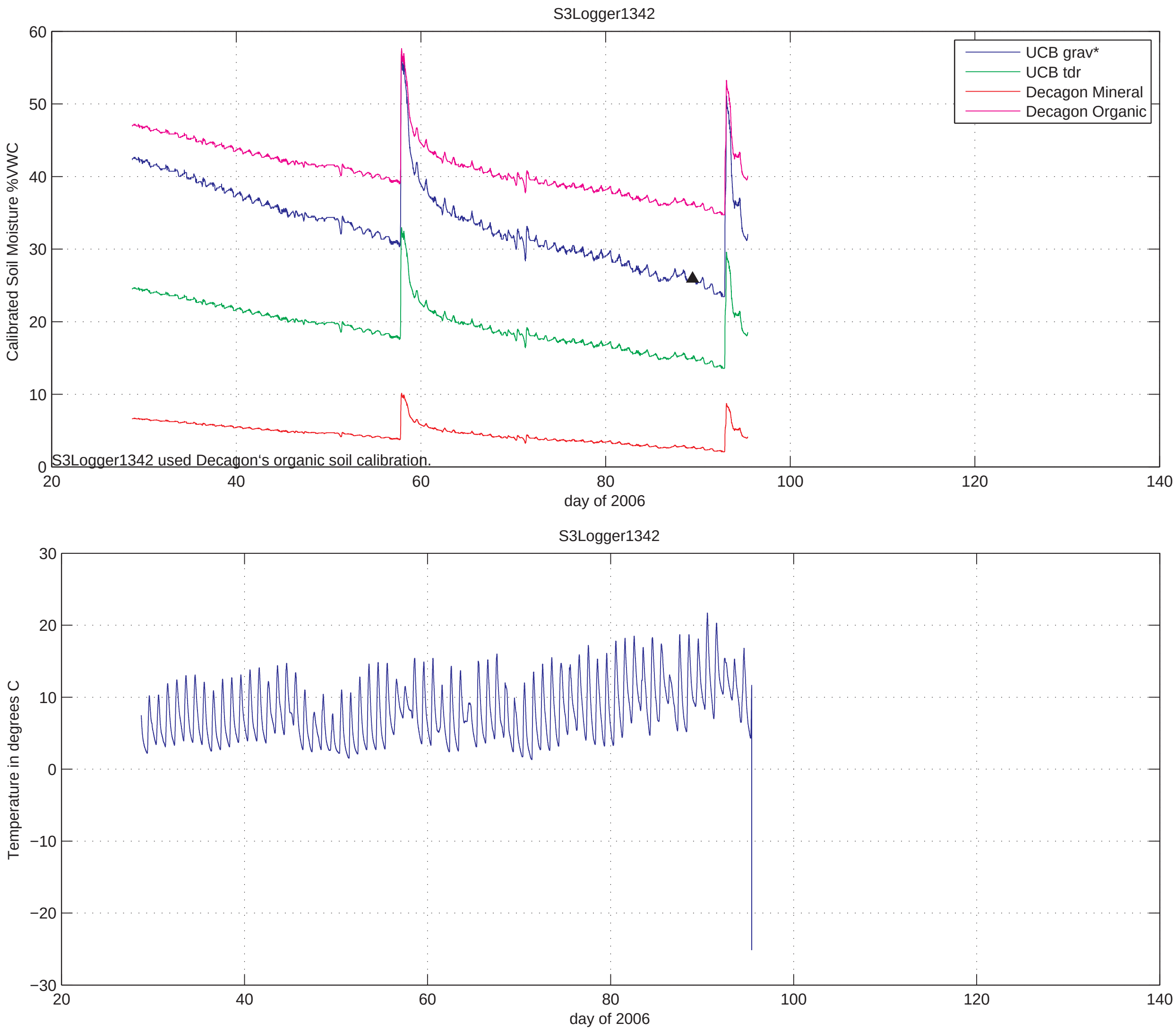


Figure 4: Data after April 6, 2006 at 9:30 AM is missing due to livestock pulling out the plugs from the data logger.

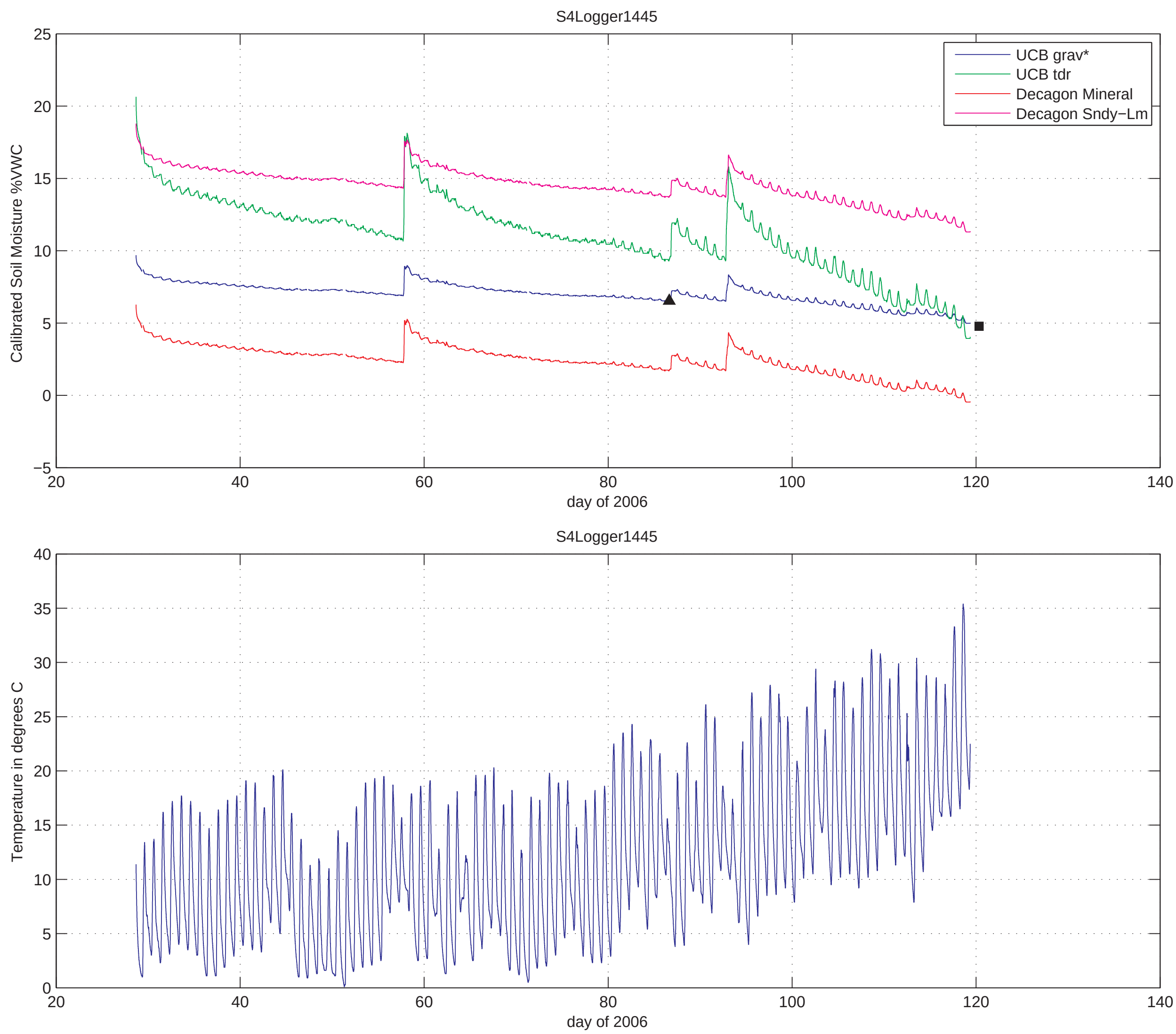

S4Logger1445
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
S4Logger1445
Temperature in degrees C
day of 2006

Figure 5:

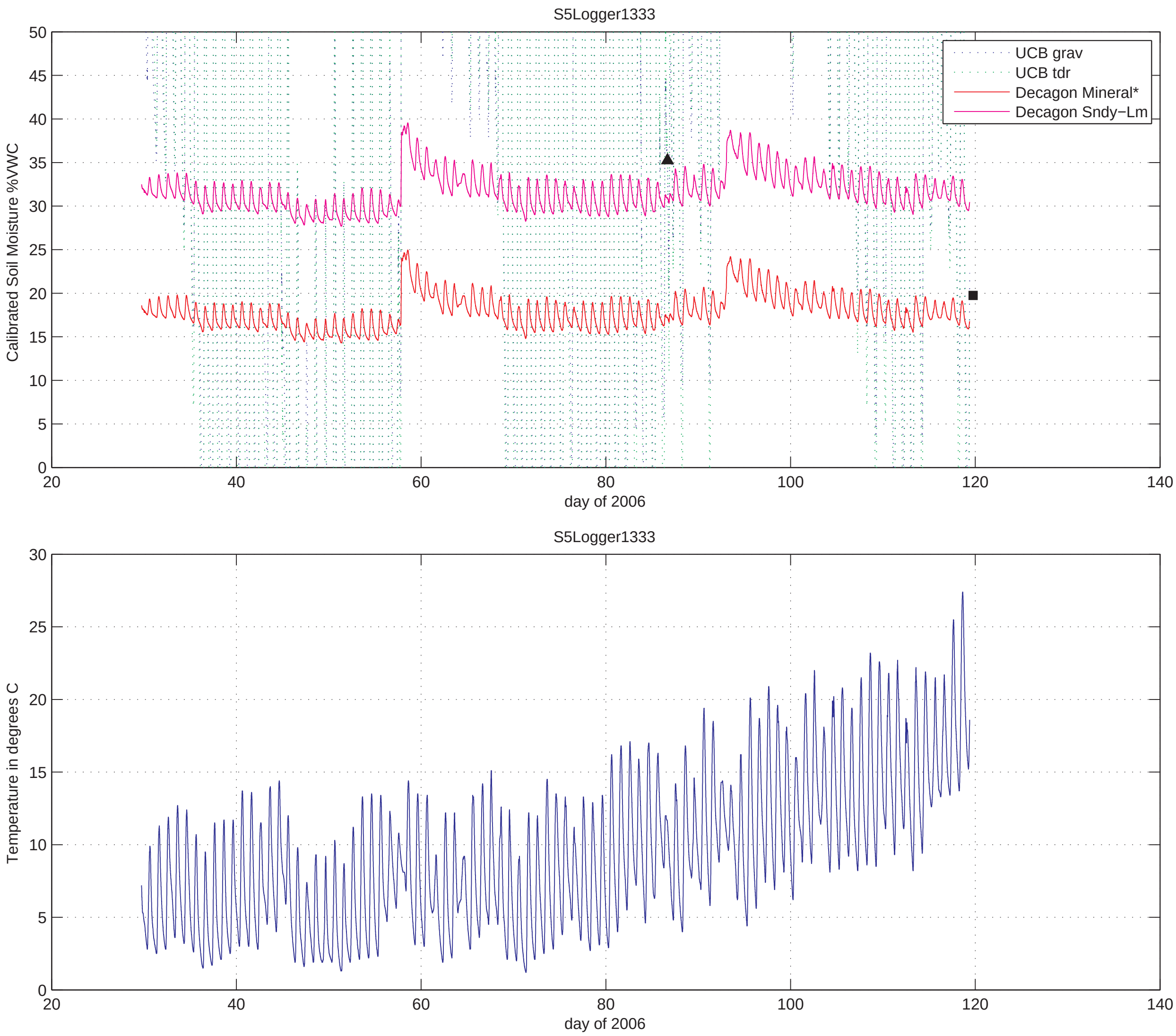


Figure 6: The Decagon Standard Mineral calibration was chosen because it most closely matched the second gravimetric measurement which was the measurement we had most confidence in. (The first set of gravimetric measurements, made in March, differed by more than 15 %VWC, the second set differed by less than 5 %VWC.) Also, the soil was determined not to contain enough sand to be considered a sandy loam. Note that the organic calibration was tested for this site, but was found to provide unreasonably high values of VWC.

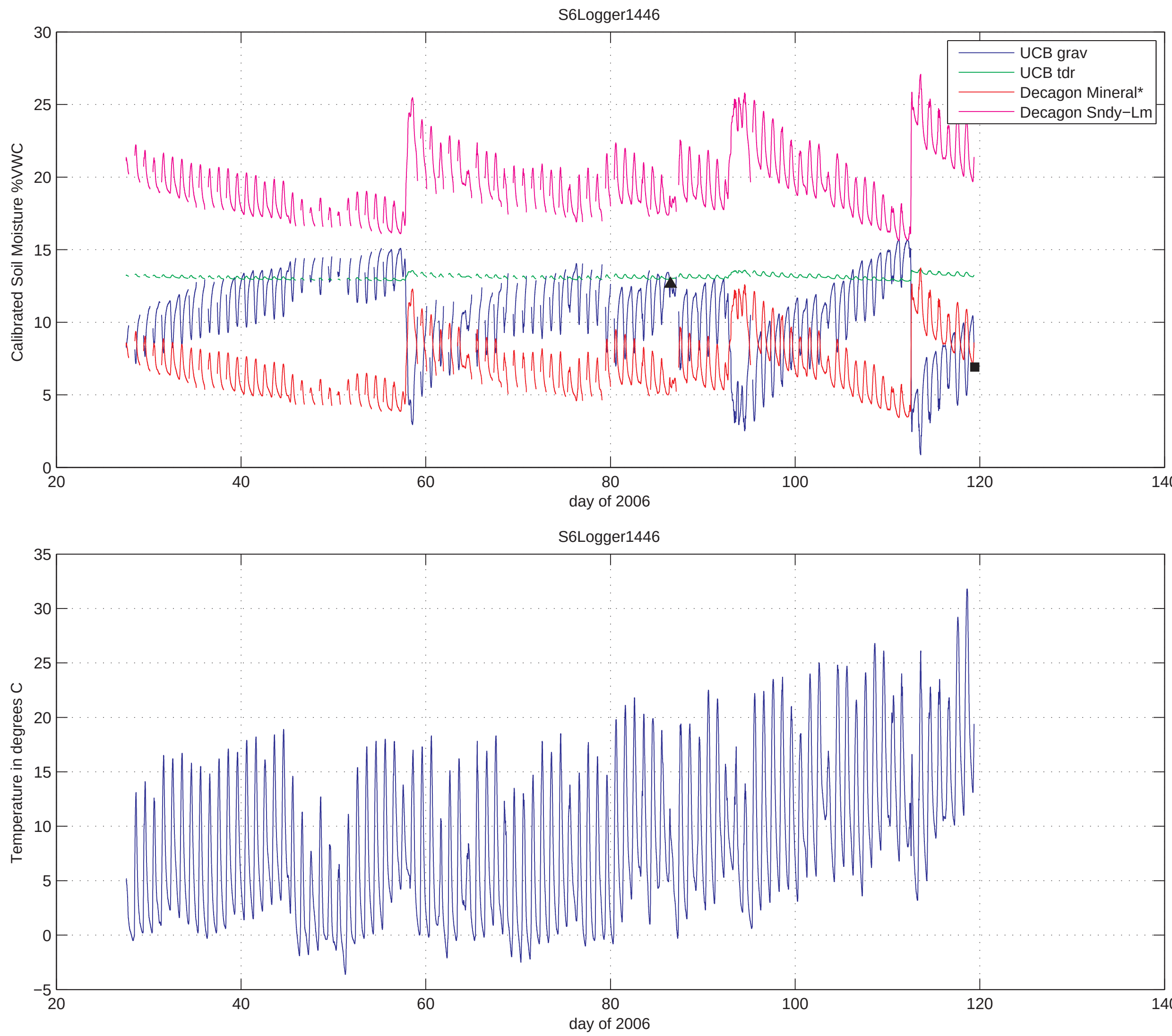


Figure 7: In two cases (S25 and S6), the gravimetric calibration yielded a slope opposite that of Decagon's standard mineral and sandy loam calibrations. This caused rain events to appear as periods of extreme drying instead of wetting, indicating that our gravimetric calibration was flawed for these sites. For S6, Decagon's standard mineral calibration was chosen because it most closely approximated the range of the gravimetric measurements taken at the site. The soil at S6 was determined to be sandy clay by touch test, so it is debatable whether the sandy loam or standard mineral calibration is better for this site.

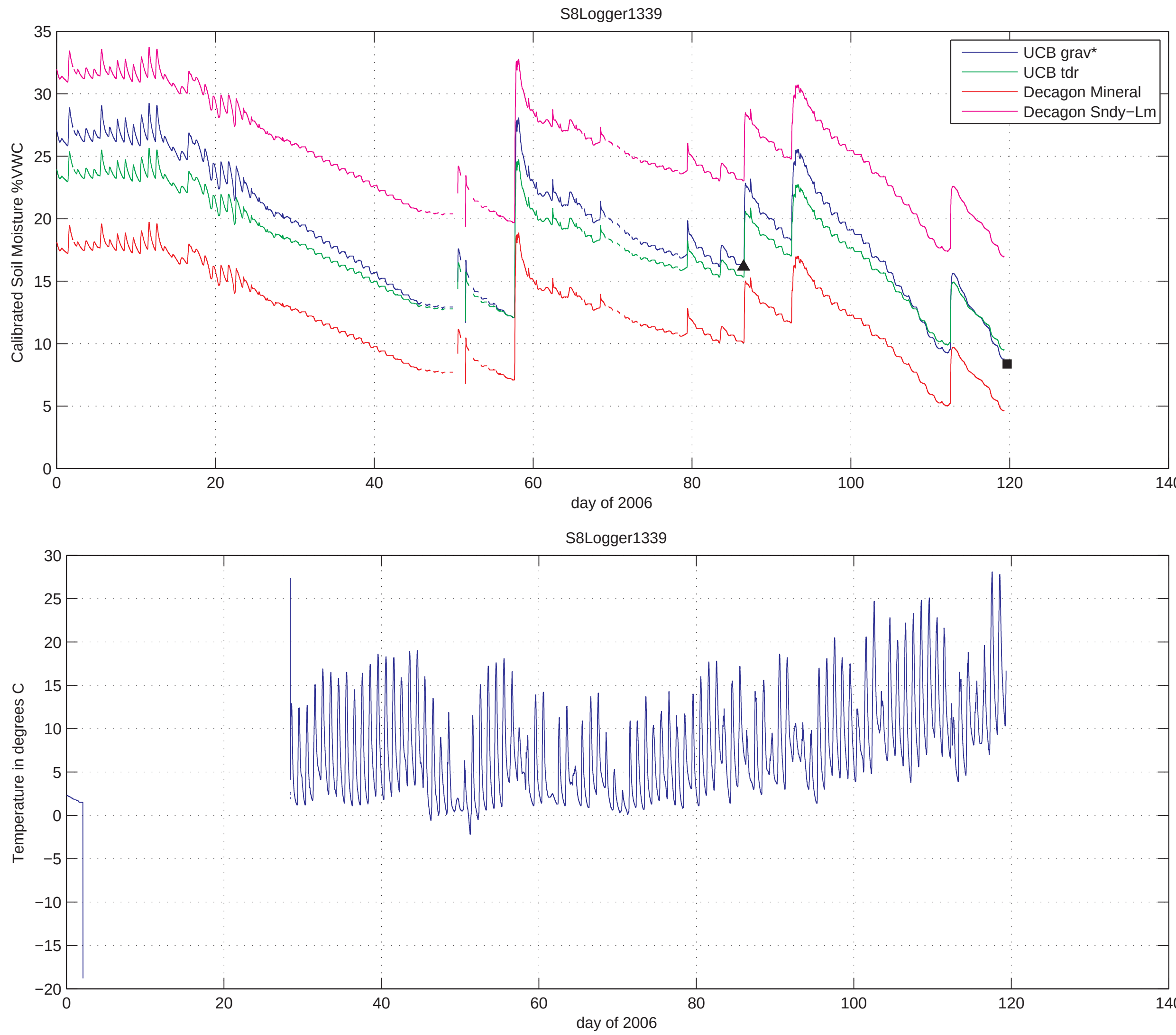
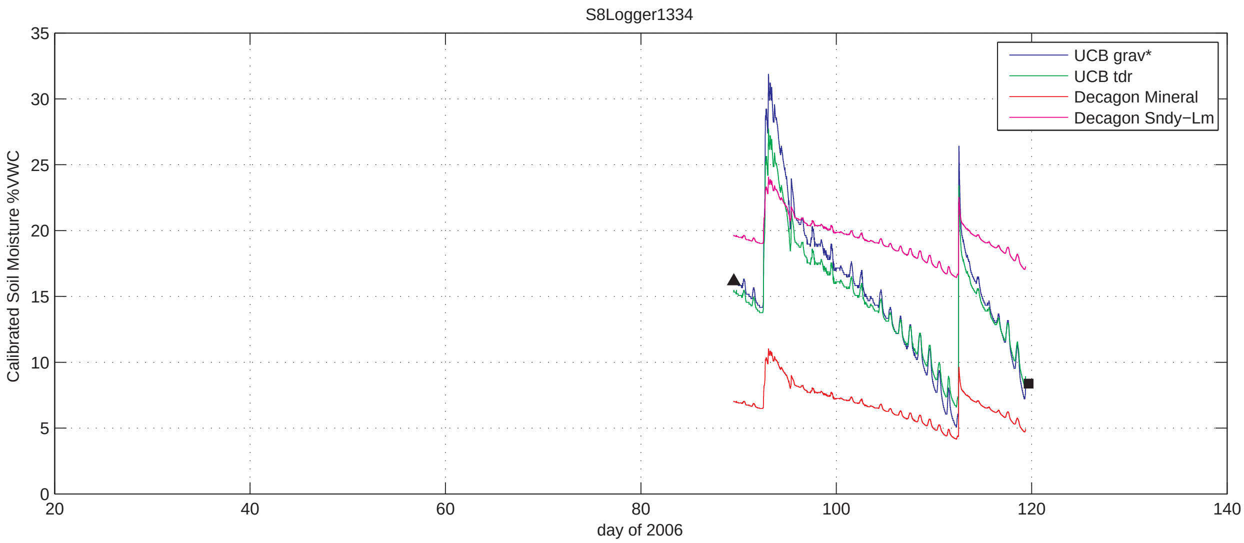


Figure 8: This sensor was installed in September. When we arrived to service the instruments at the end of January we found that the plug for the temperature gage had become disconnected from the data logger.



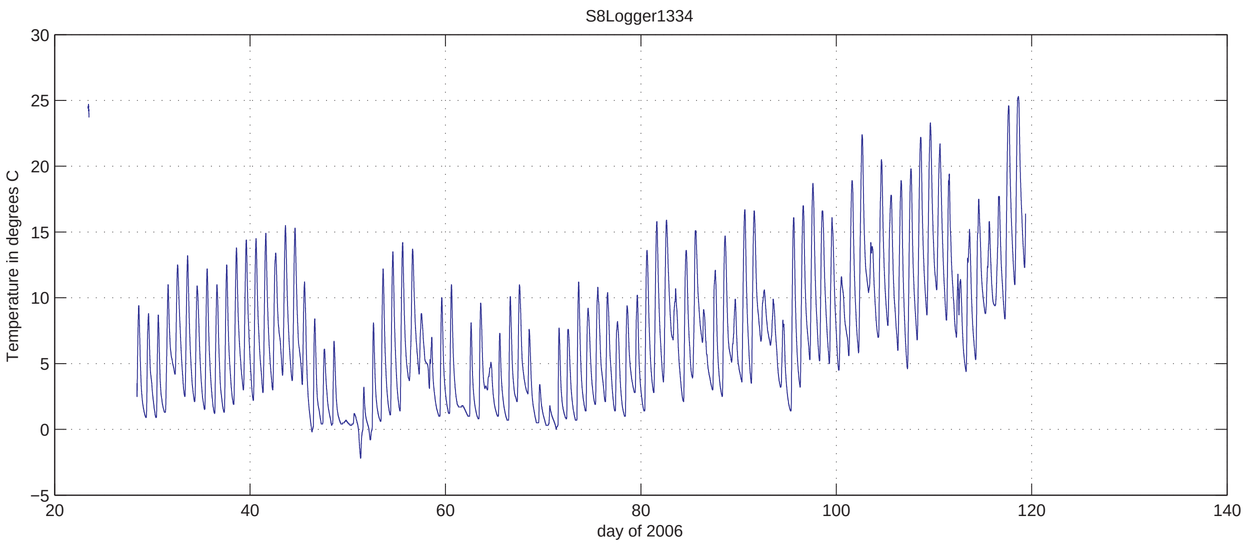


Figure 9: Logger 1334 recorded spurious data (not shown) after it was installed at the end of January until it was serviced at the end of March. We are not sure why it began recording reasonable data again after servicing it in March. It could be that the sensor was not fully plugged into the logger in January.

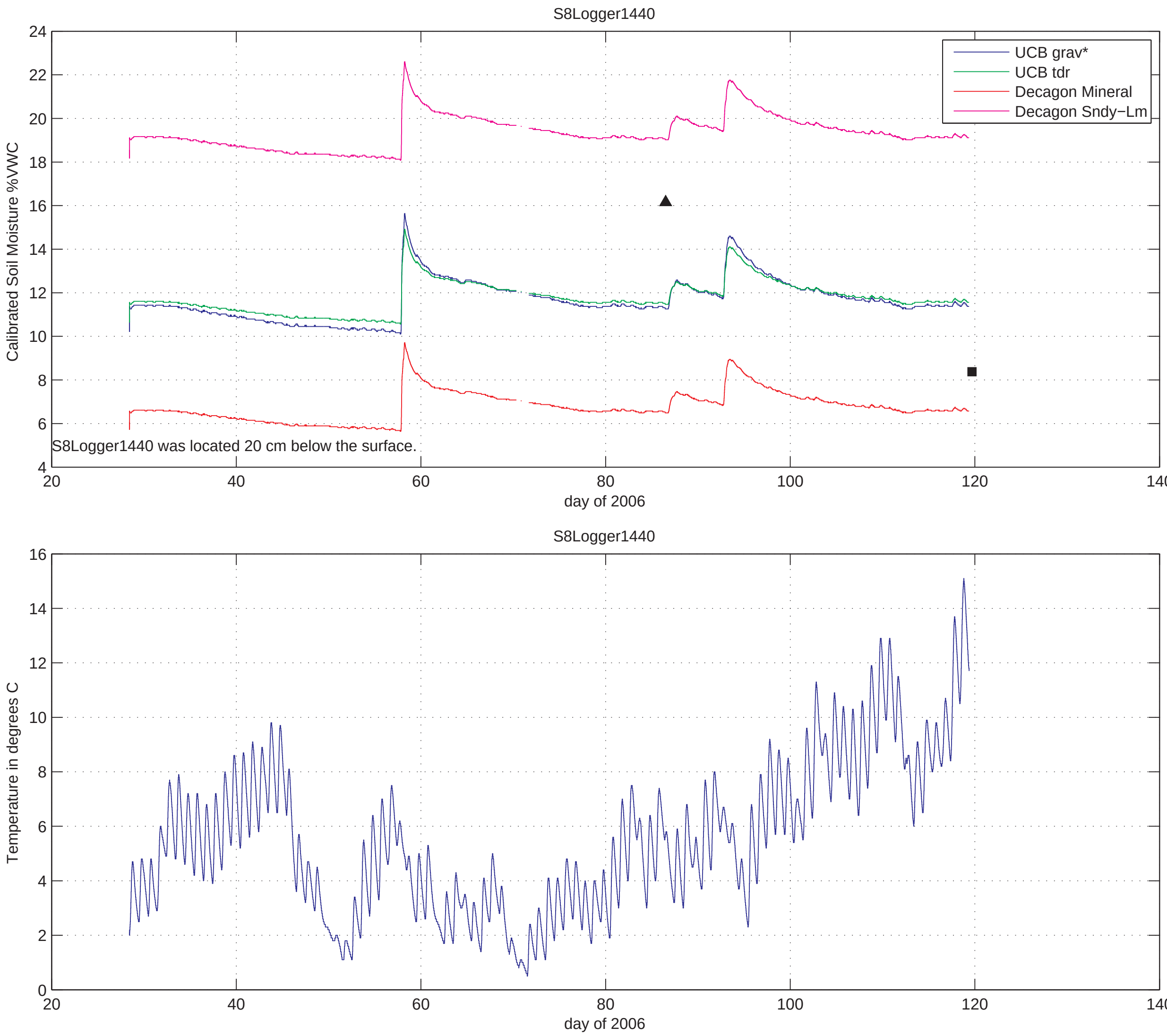
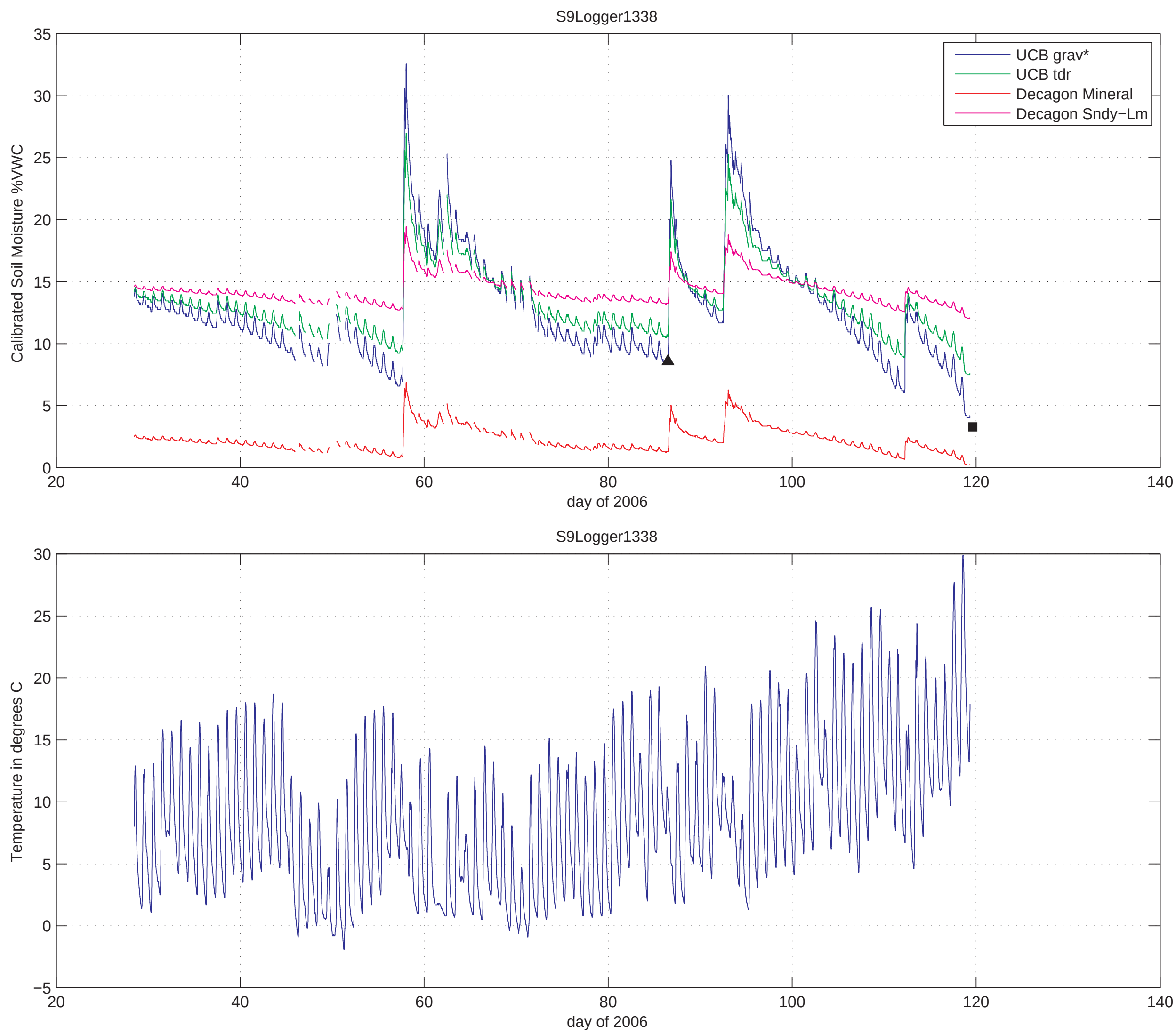


Figure 10: The sensor connected to Logger 1440 was buried at a depth of 20 cm, so the calibration from the sensor at 5 cm connected to Logger 1339 was used. For this reason the black symbols representing the gravimetric measurements do not match the values of the blue line representing the gravimetric calibration on this figure.



S9Logger1338
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
S9Logger1338
Temperature in degrees C
day of 2006

Figure 11:

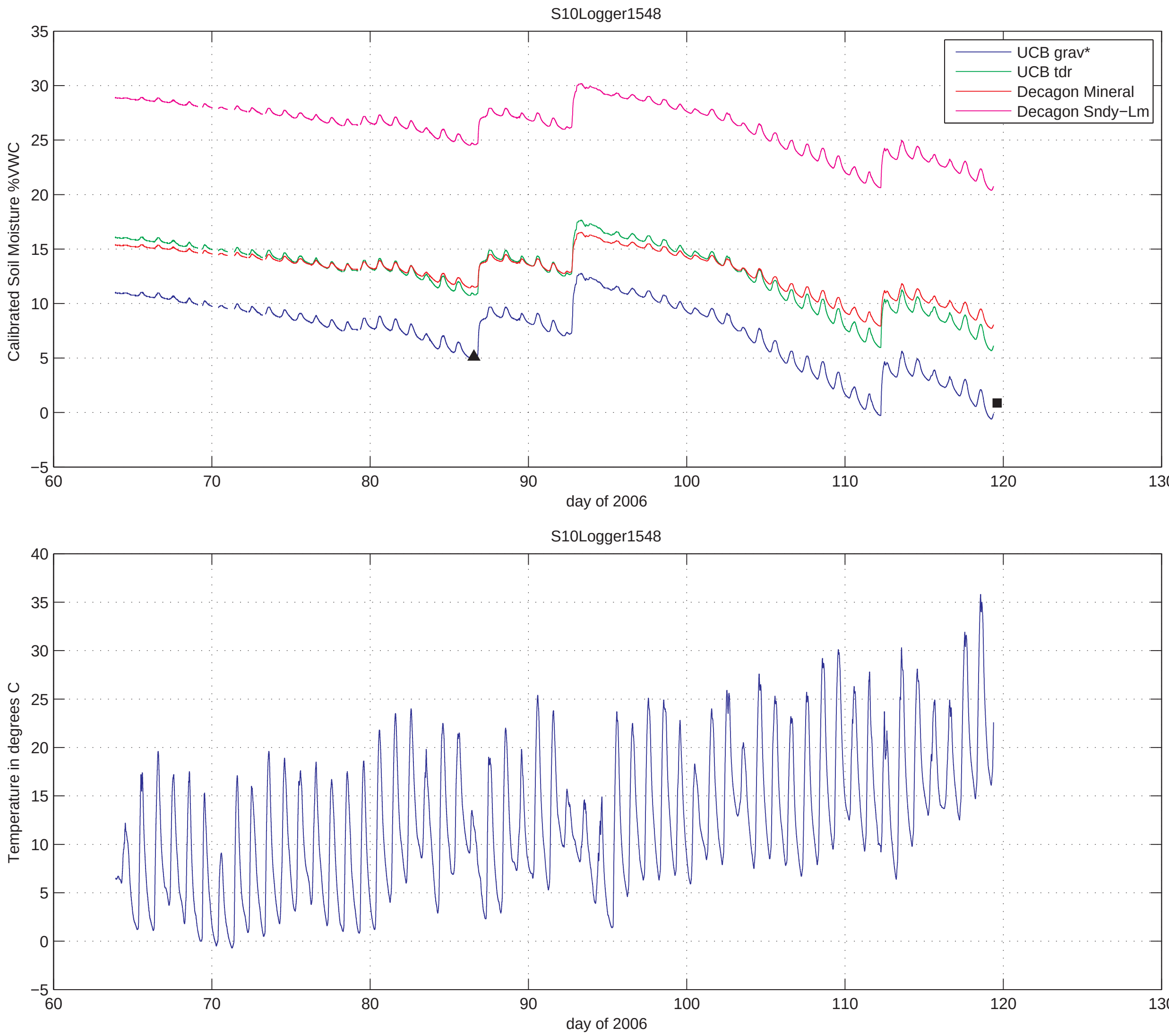

S10Logger1548
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
Calibrated Soil Moisture %VWC
day of 2006
S10Logger1548
Temperature in degrees C
day of 2006

Figure 12:

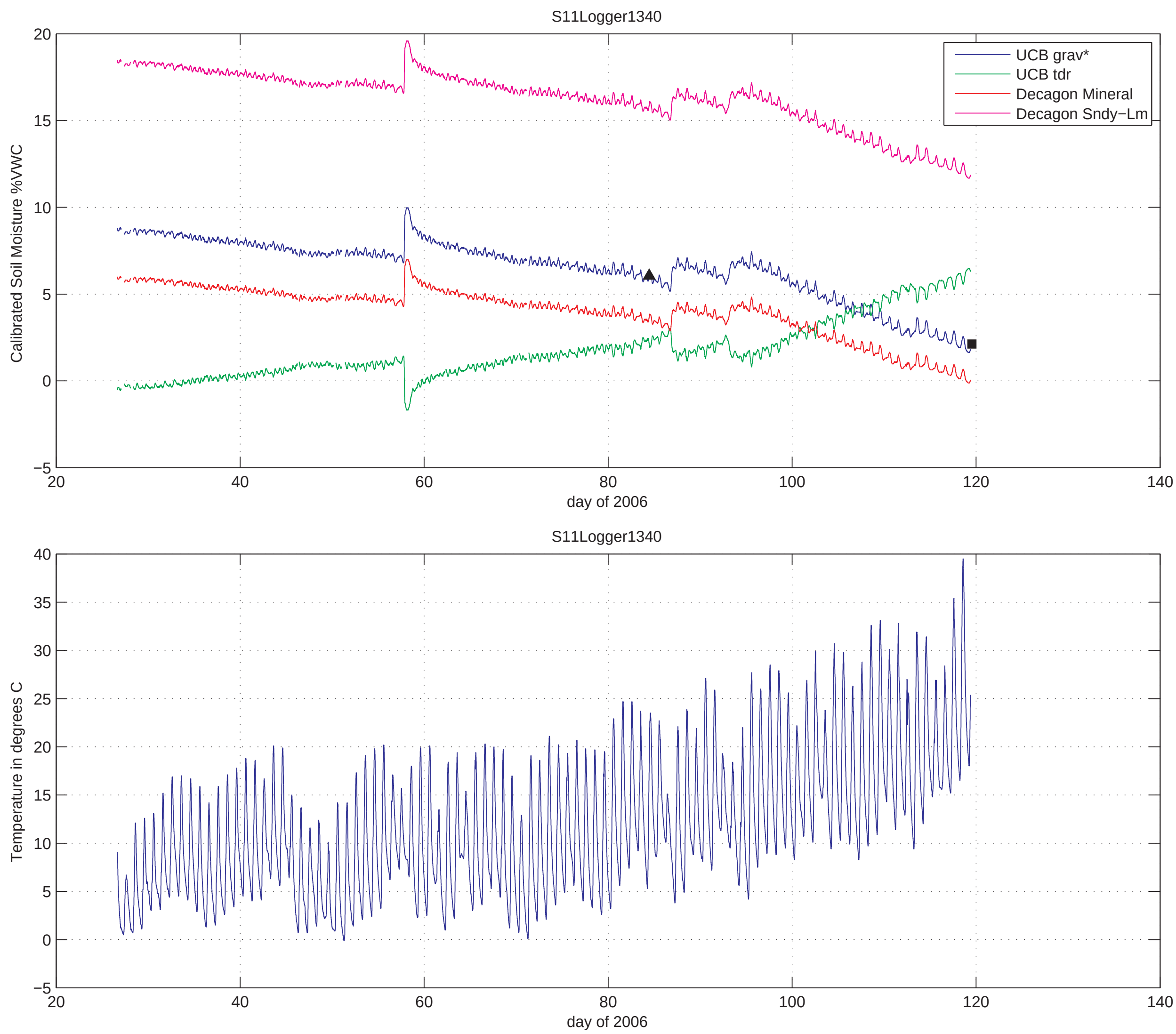

S11Logger1340
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
Calibrated Soil Moisture %VWC
20
15
10
5
0
−5
20
40
60
80
100
120
140
day of 2006
S11Logger1340
Temperature in degrees C
40
35
30
25
20
15
10
5
0
−5
20
40
60
80
100
120
140
day of 2006

Figure 13:

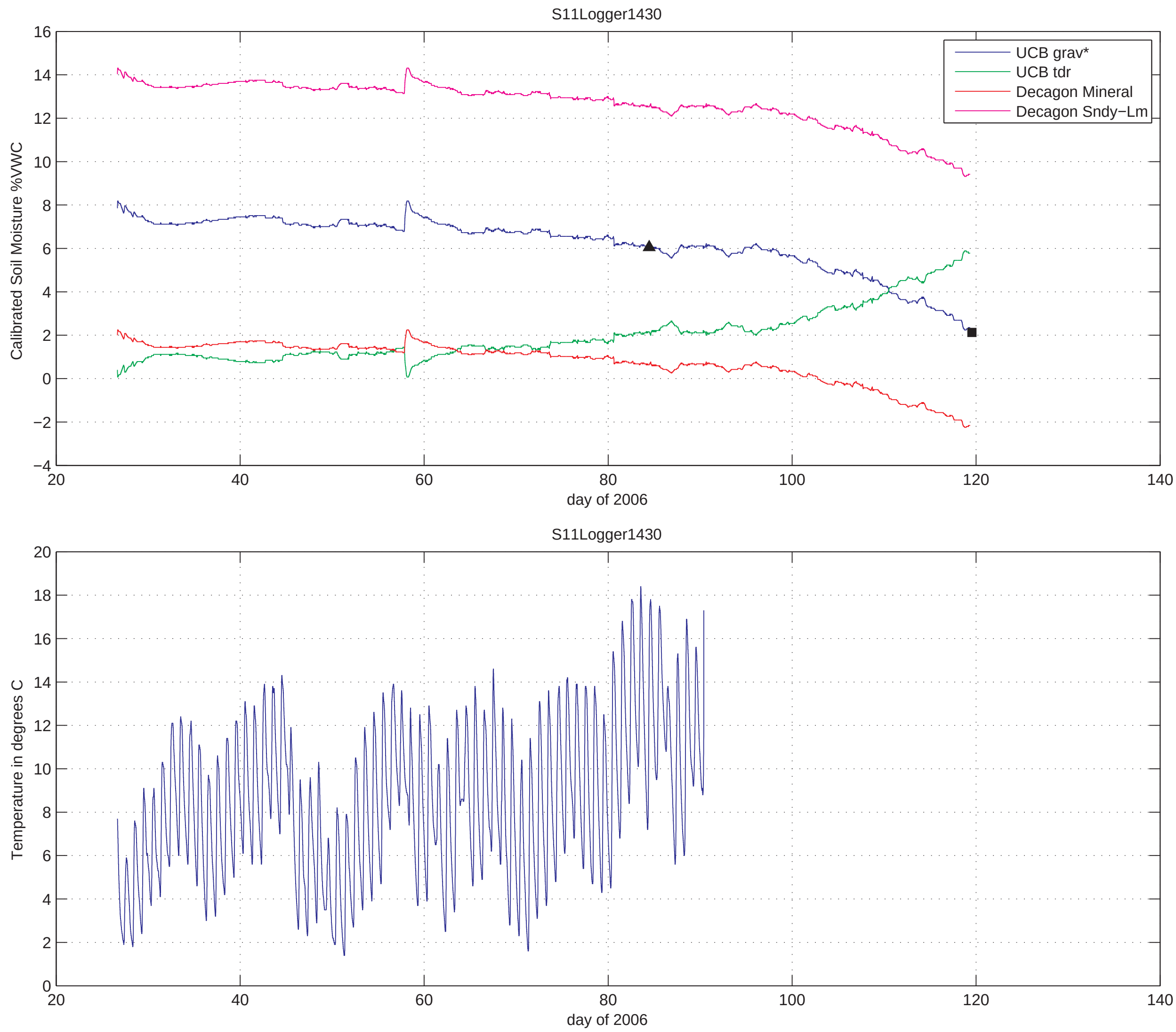
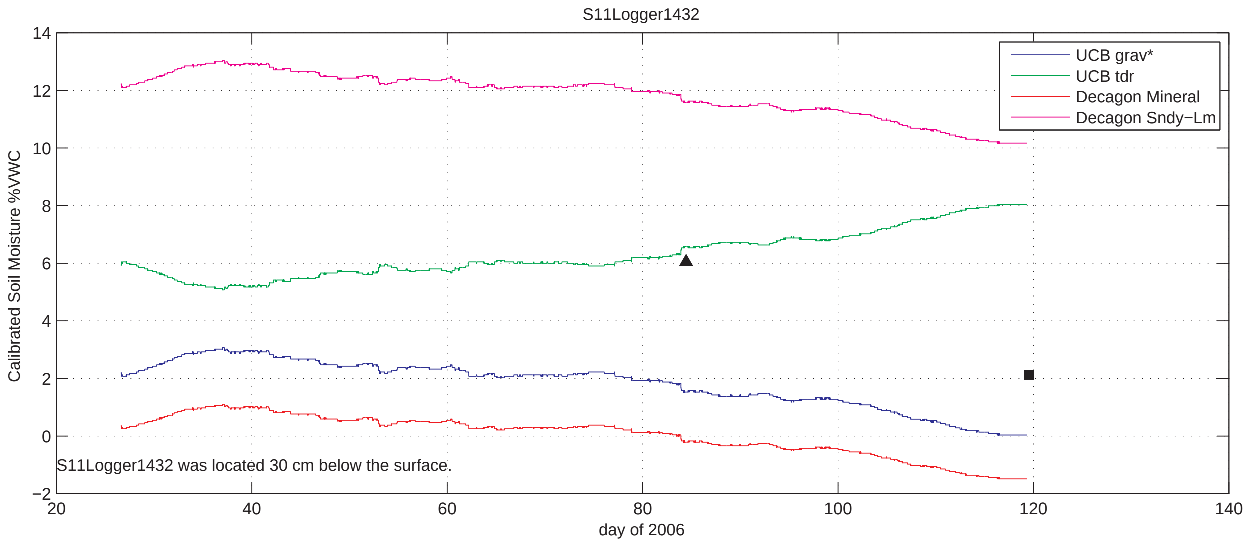


Figure 14: The temperature probe was unplugged from Logger 1430 when the instruments were retrieved in April, so temperature data is missing for the last month. Fortunately, Logger 1340 was also at the site and sucessfully recorded temperature at 5 cm depth.



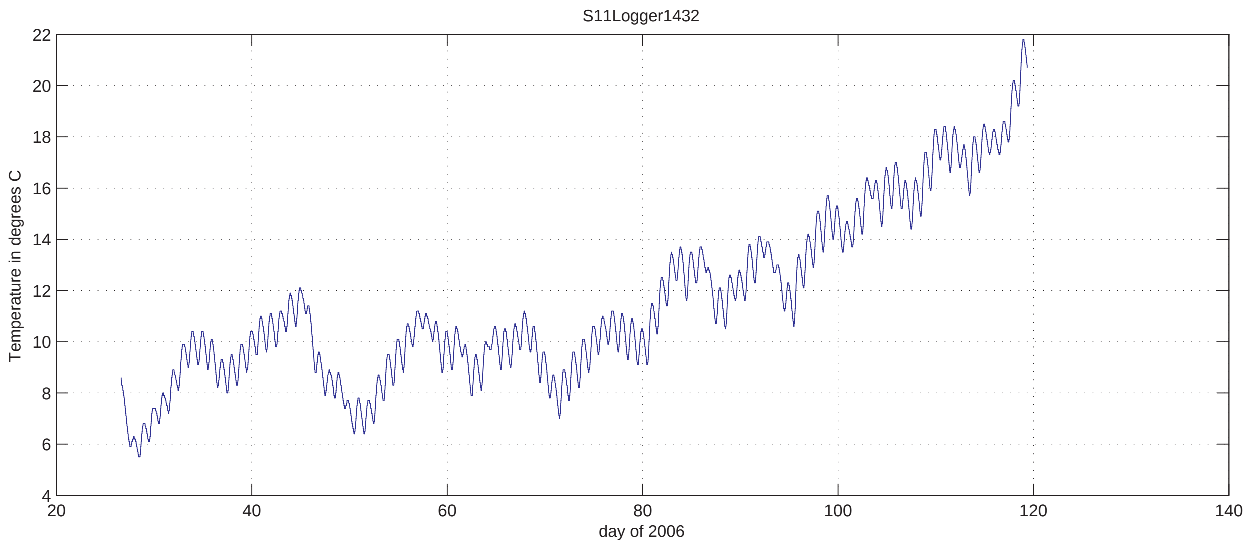
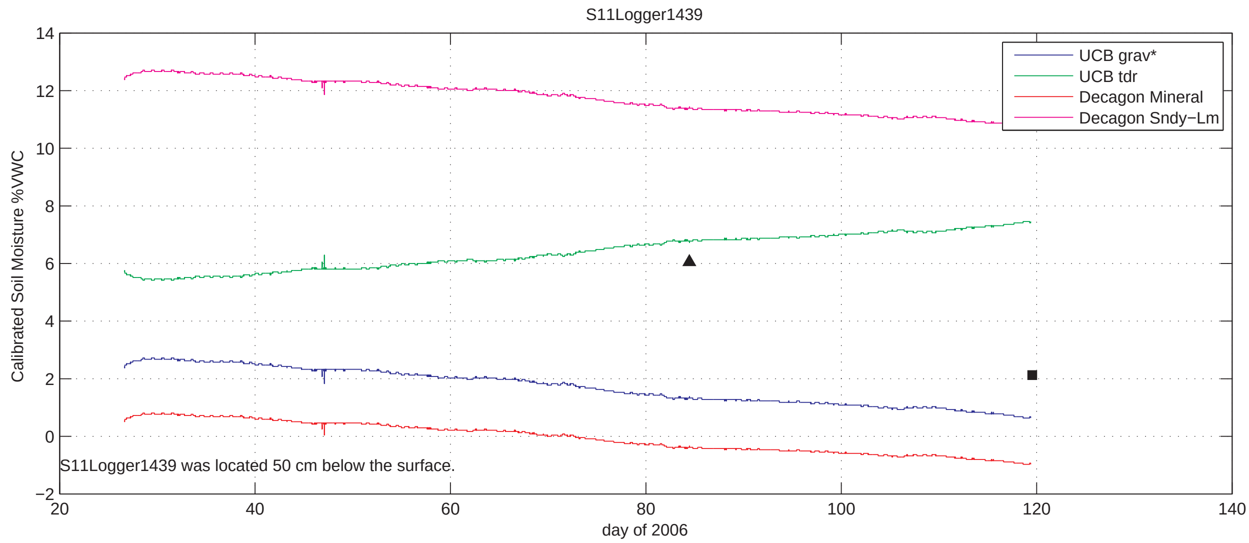


Figure 15: The sensor connected to Logger 1432 was buried at a depth of 30 cm, so the calibration from the sensor at 5 cm connected to Logger 1340 was used. For this reason the black symbols representing the gravimetric measurements do not match the values of the blue line representing the gravimetric calibration on this figure.



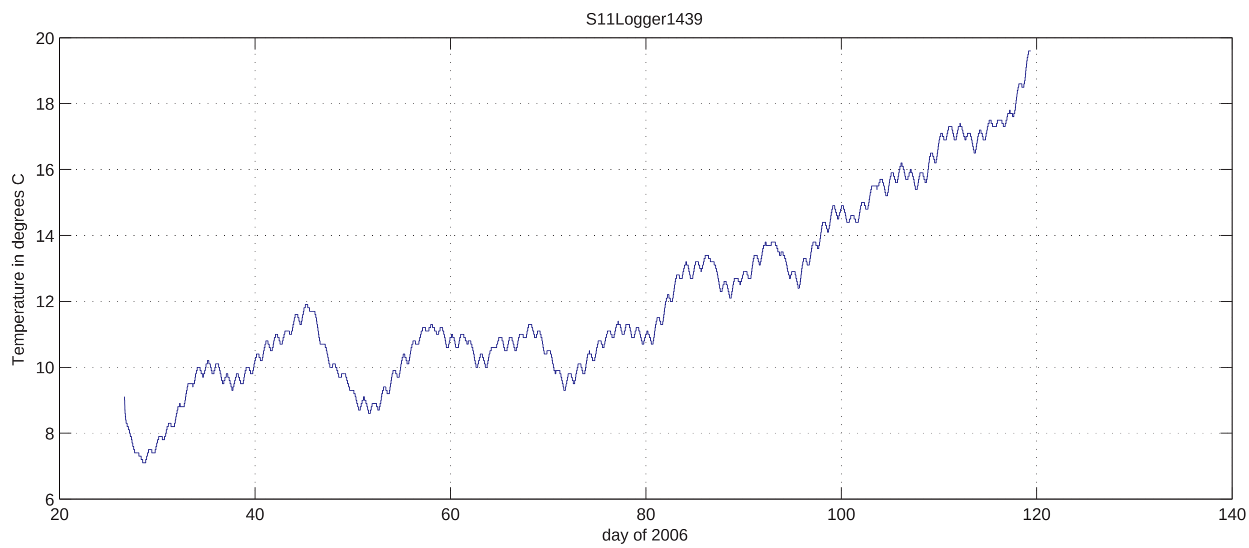


Figure 16: The sensor connected to Logger 1439 was buried at a depth of 50 cm, so the calibration from the sensor at 5 cm connected to Logger 1340 was used. For this reason the black symbols representing the gravimetric measurements do not match the values of the blue line representing the gravimetric calibration on this figure.

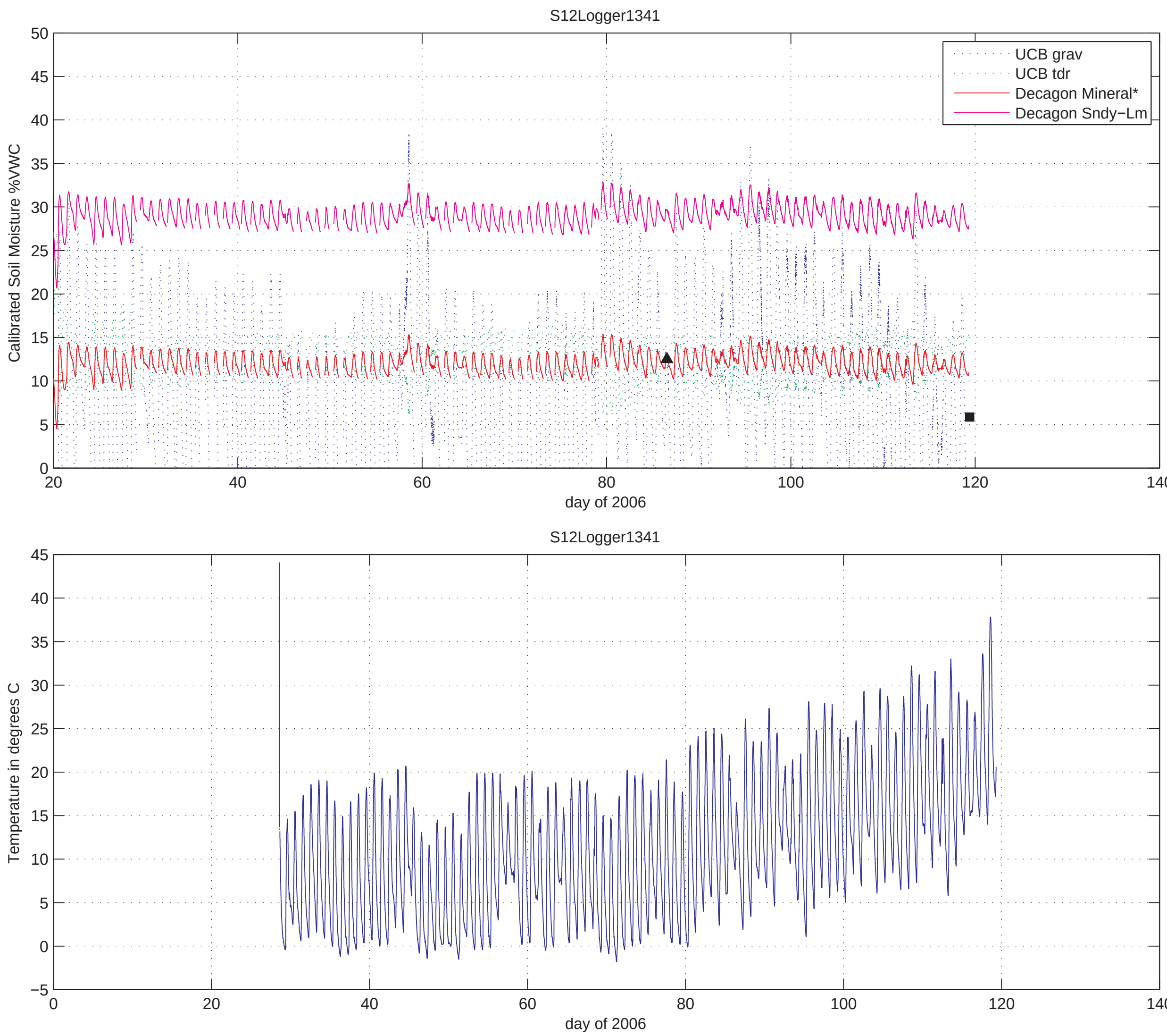
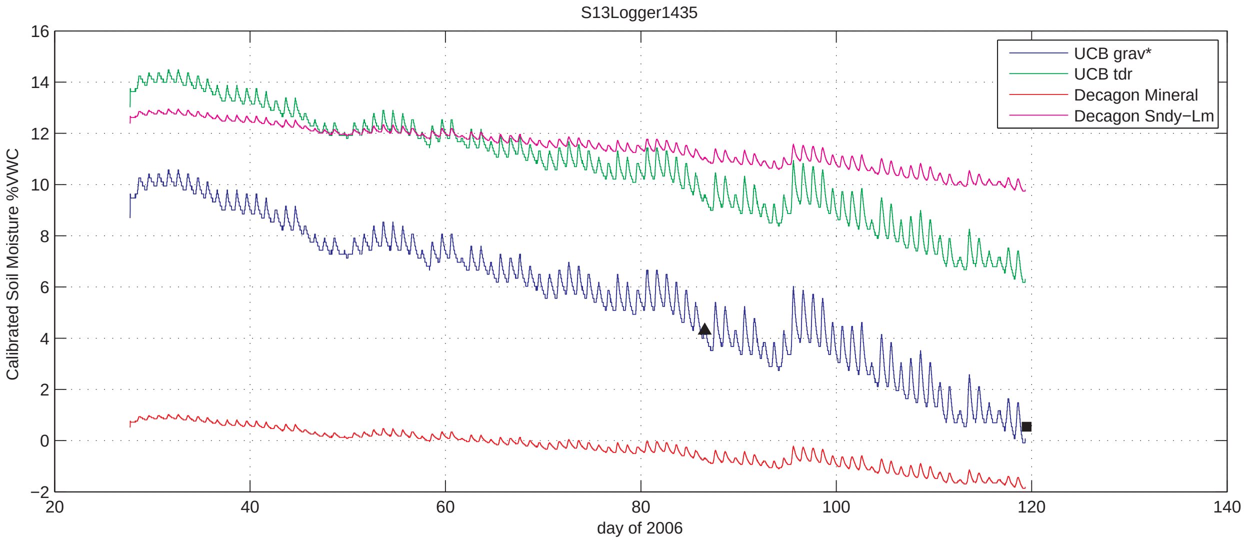
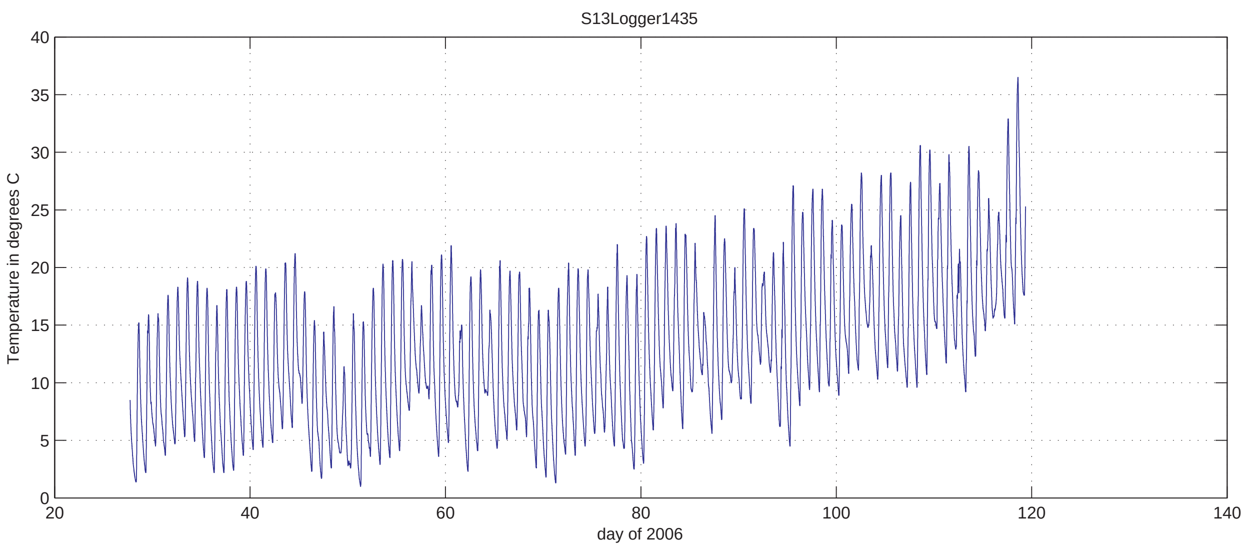


Figure 17: A Decagon Standard Mineral adjusted calibration was chosen because it provided values that were closest to our gravimetric measurements. We had most confidence in the first set of gravimetric measurements which differed by only 0.65 %VWC while the second set differed by 2.88 %VWC. In this case, we used the slope of Decagon's standard calibration curve and adjusted the y-intercept so that the calibration matches at the first gravimetric measurement. (Before this adjustment was made, the standard calibration curve yielded values about 3 %VWC higher on average than the adjusted curve shown above.) The temperature probe for Logger 1341 was unplugged when we arrived to service the instruments at the end of January, so there was no temperature data recorded until that time.



S13Logger1435
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
Calibrated Soil Moisture %VWC
day of 2006



S13Logger1435
Temperature in degrees C
day of 2006

Figure 18:

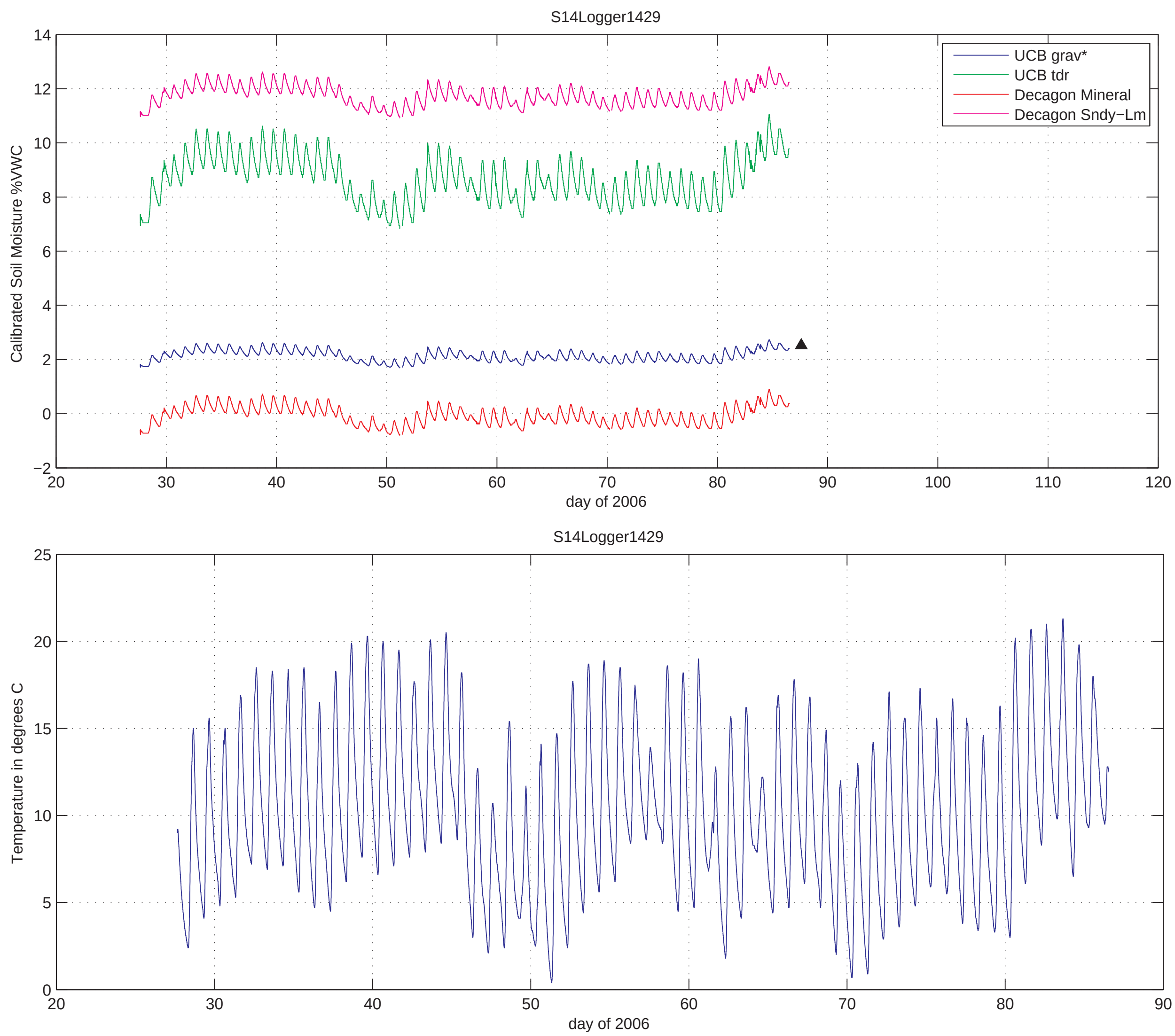


Figure 19: Logger 1429 had problems with its circuitry and had to be returned to Decagon Devices for repair. Unfortunately none of the data for the month of April was salvaged. The data shown here were downloaded from the logger in the field before it malfunctioned. We only took one set of gravimetric measurements for this site.

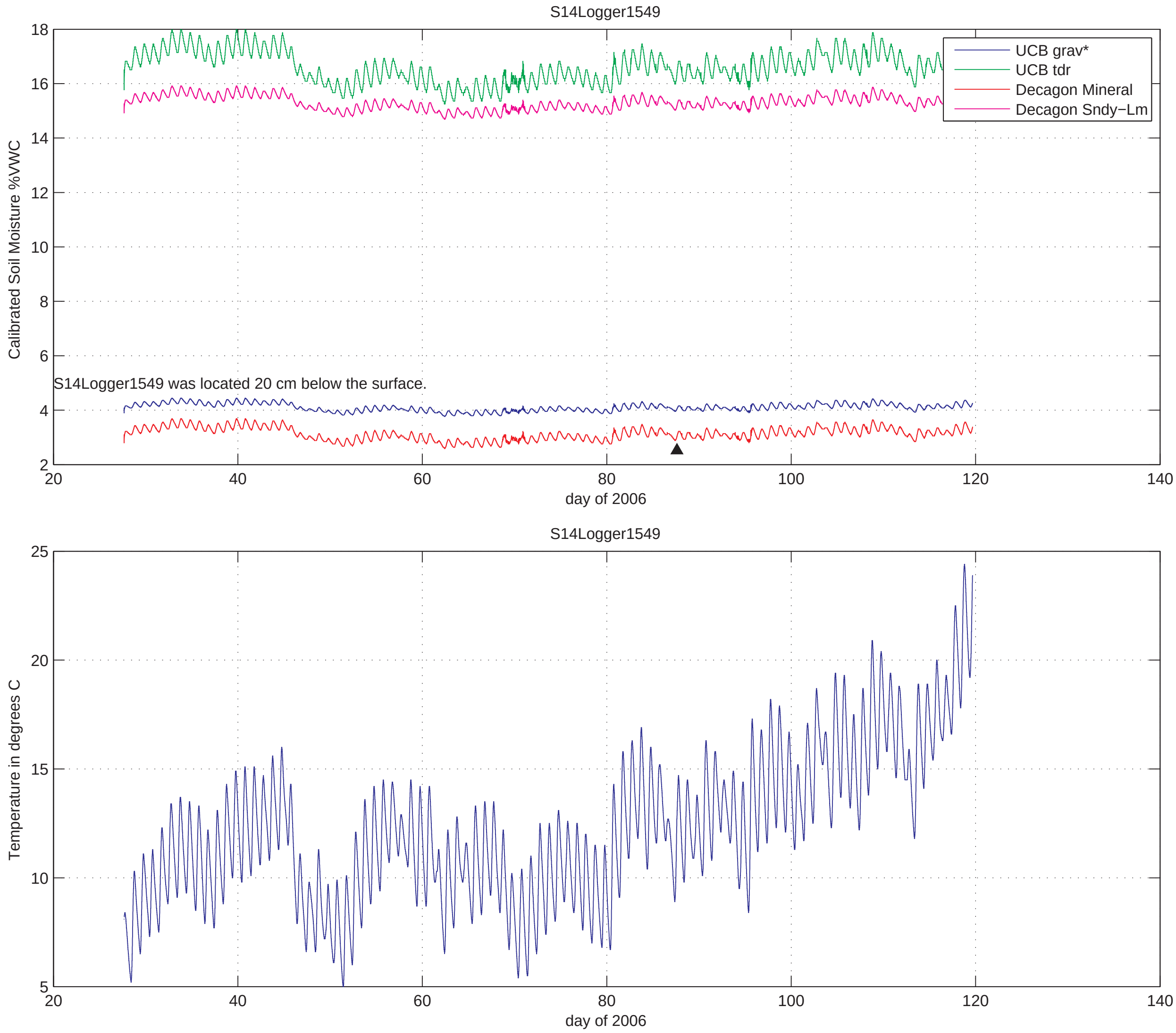
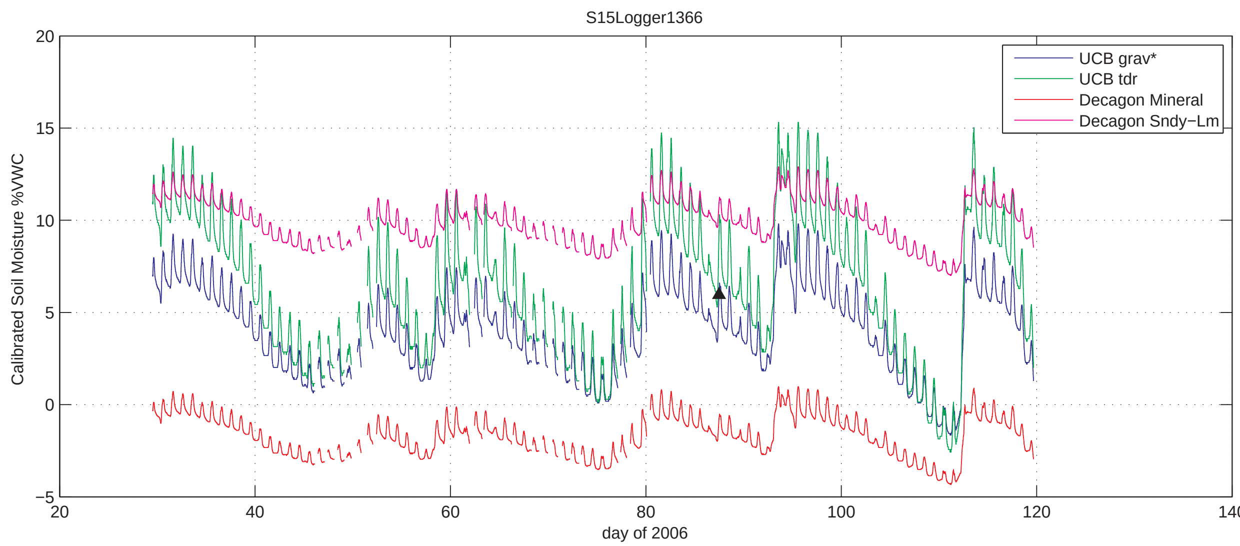


Figure 20: We only took one set of gravimetric measurements for this site.



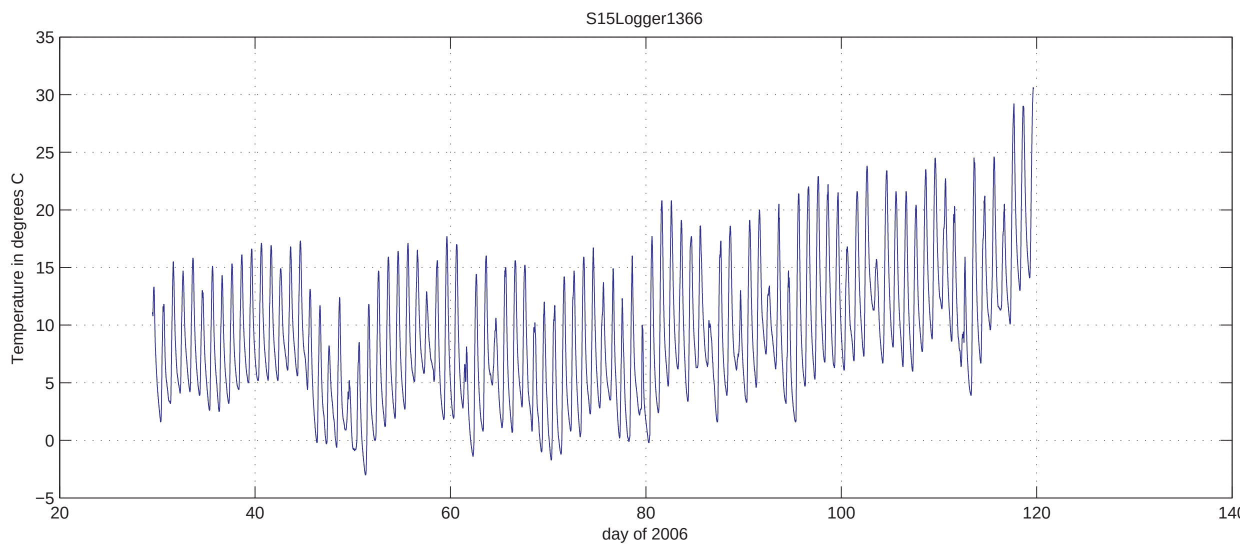


Figure 21: We only took one set of gravimetric measurements for this site.

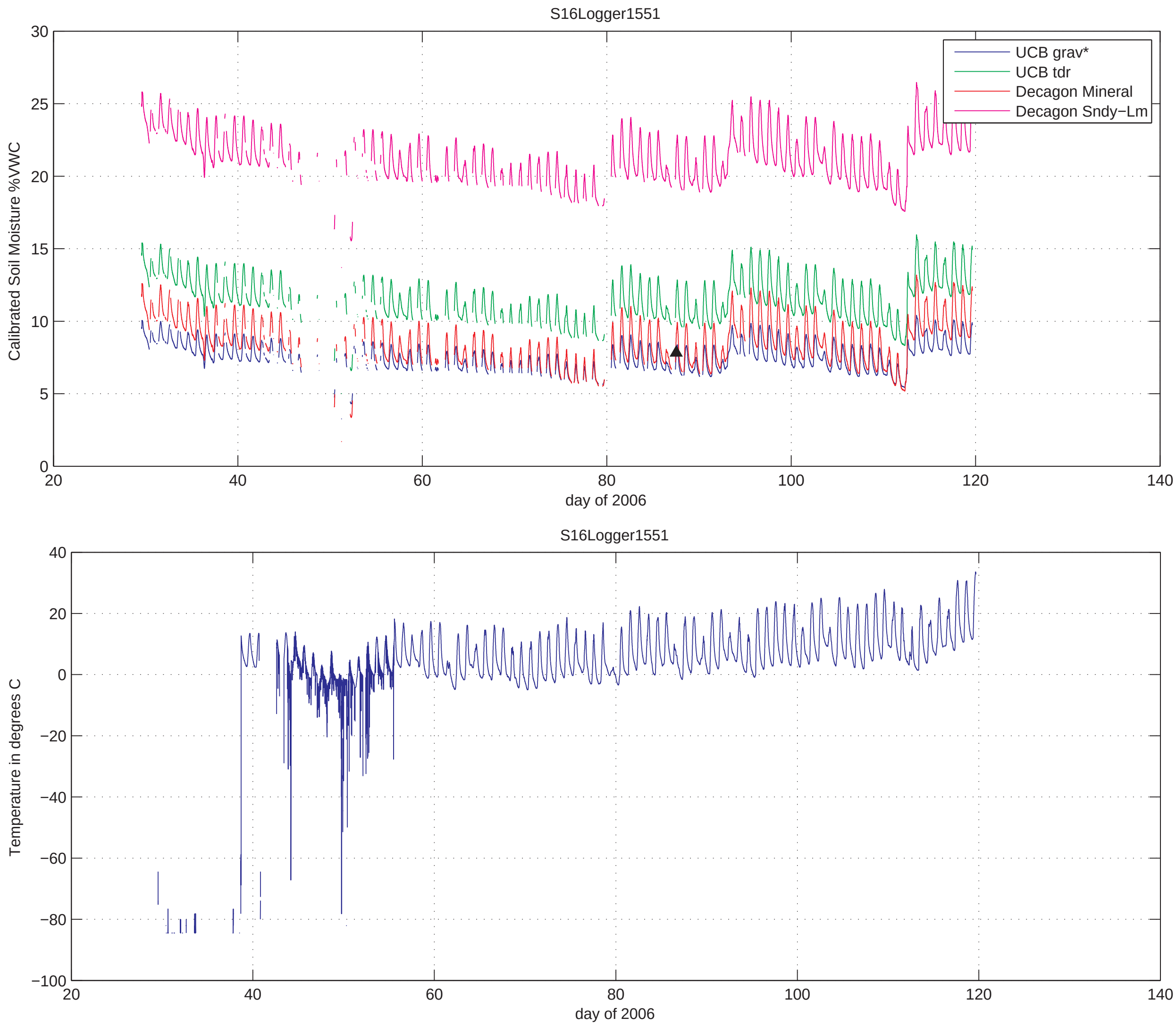
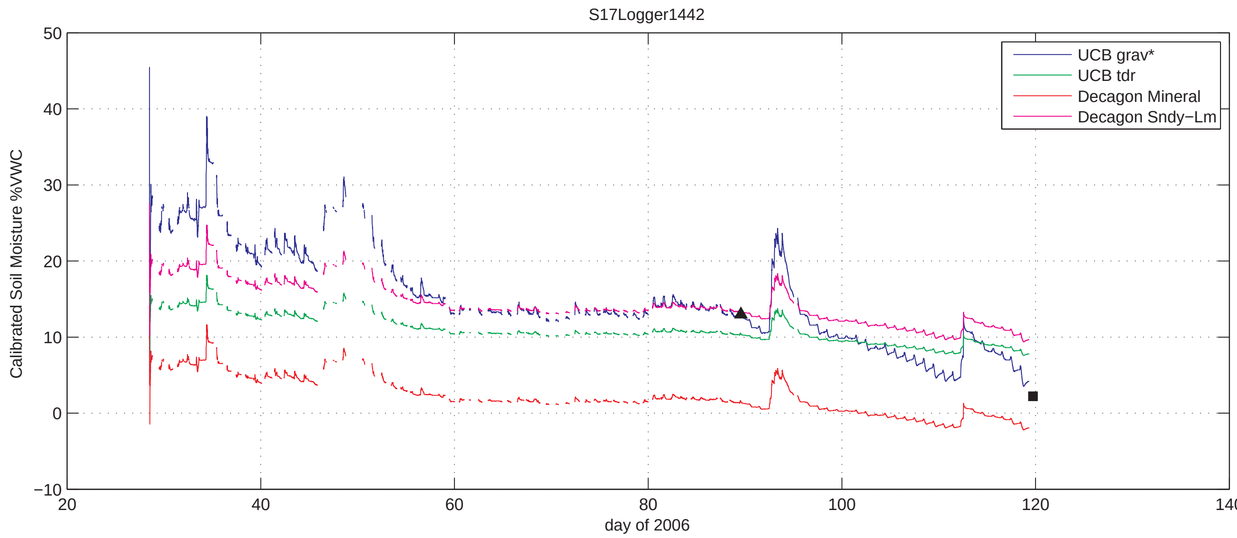


Figure 22: Below freezing temperatures appear to have caused spurious temperature readings, though according to Decagon the temperature probe should have been capable of functioning normally in the range of temperatures from -40 °C to 60 °C. We only took one set of gravimetric measurements for this site.


S17Logger1442
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
50
40
30
20
10
0
−10
20
40
60
80
100
120
140

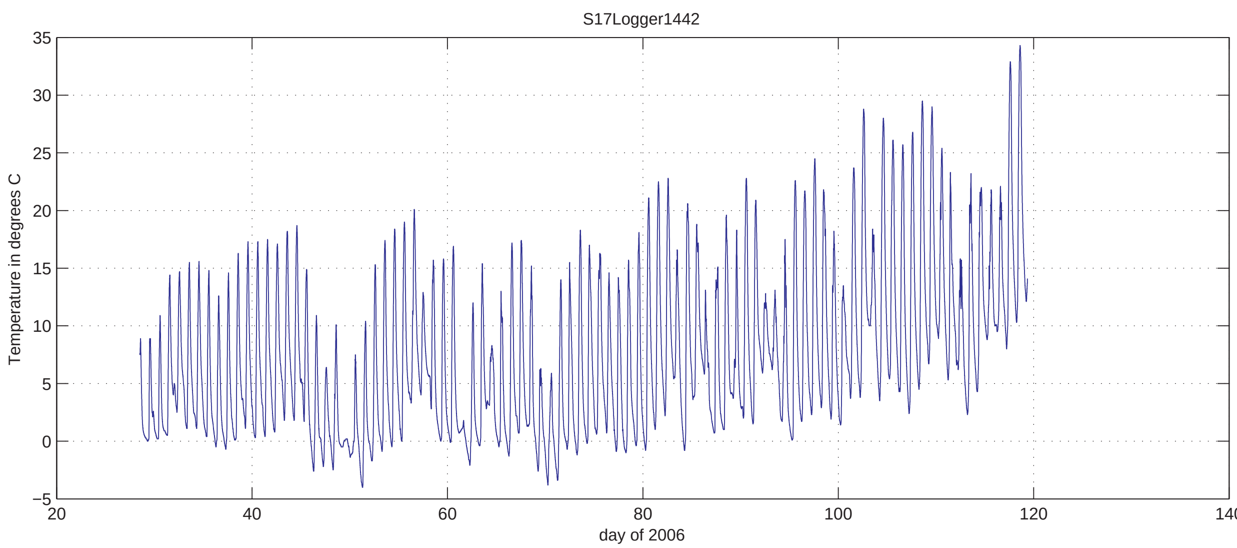

S17Logger1442
Temperature in degrees C
day of 2006
35
30
25
20
15
10
5
0
−5
20
40
60
80
100
120
140

Figure 23:

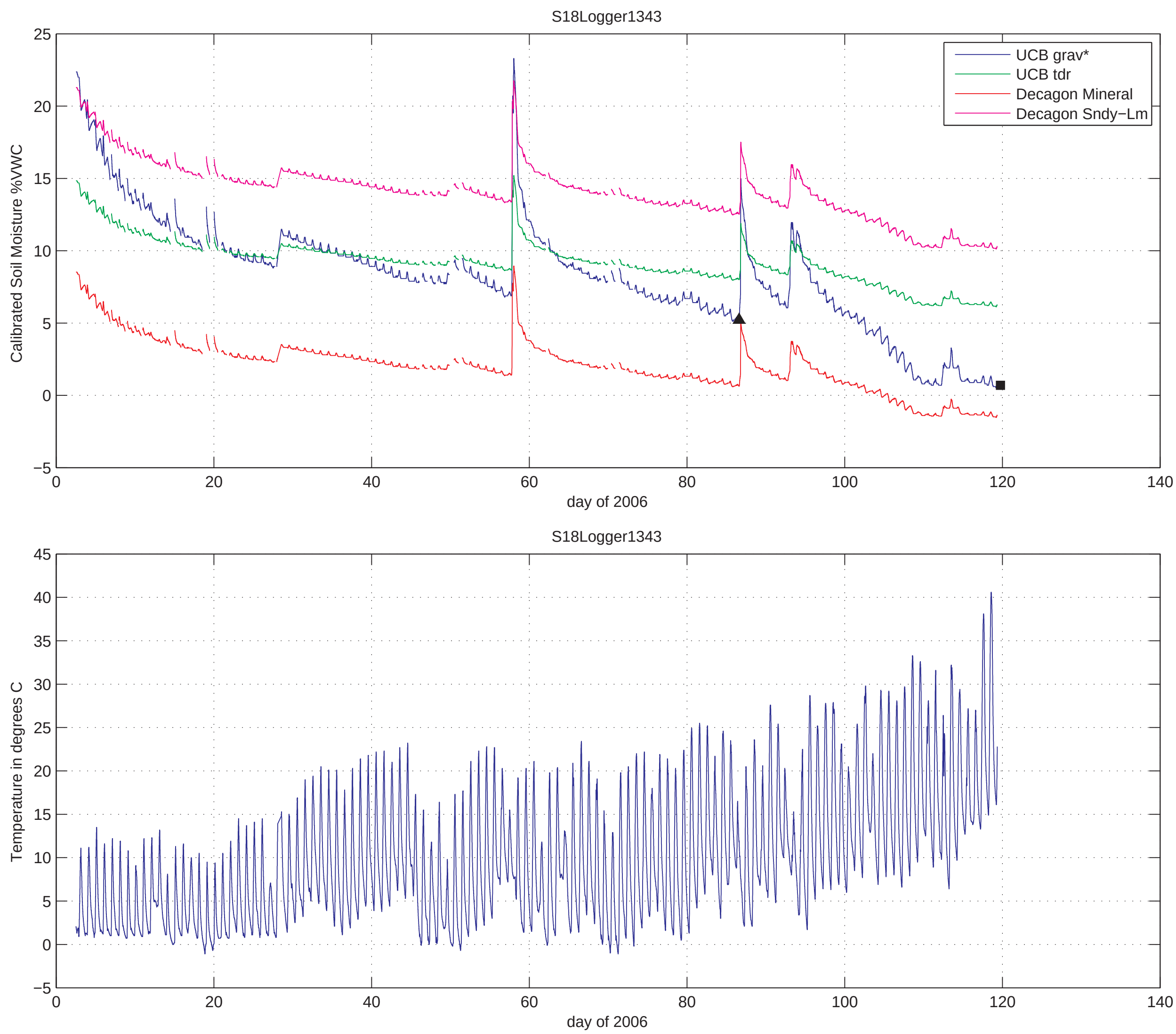

S18Logger1343
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
S18Logger1343
Temperature in degrees C
day of 2006

Figure 24:

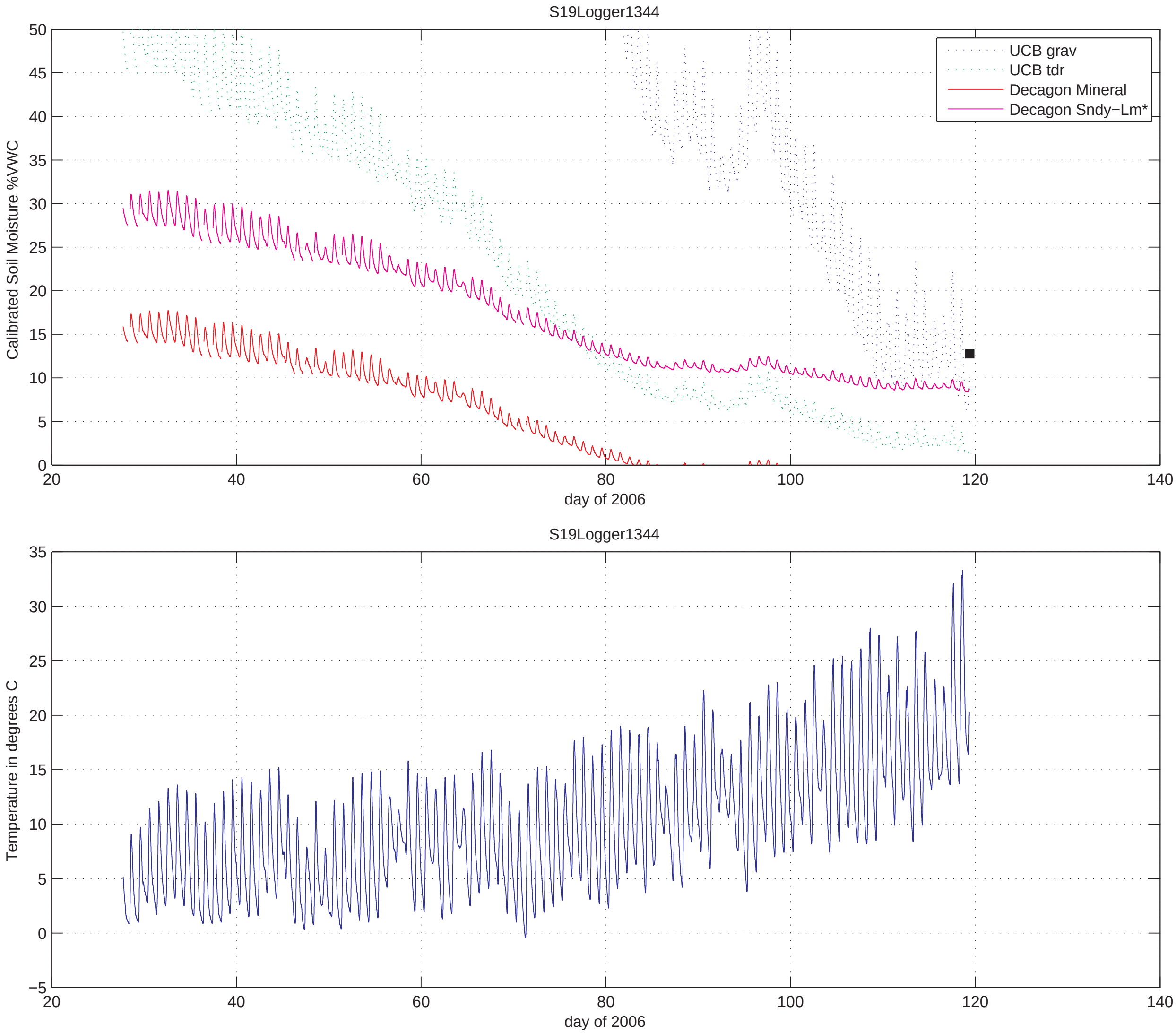


Figure 25: We only took one set of gravimetric measurements for this site.

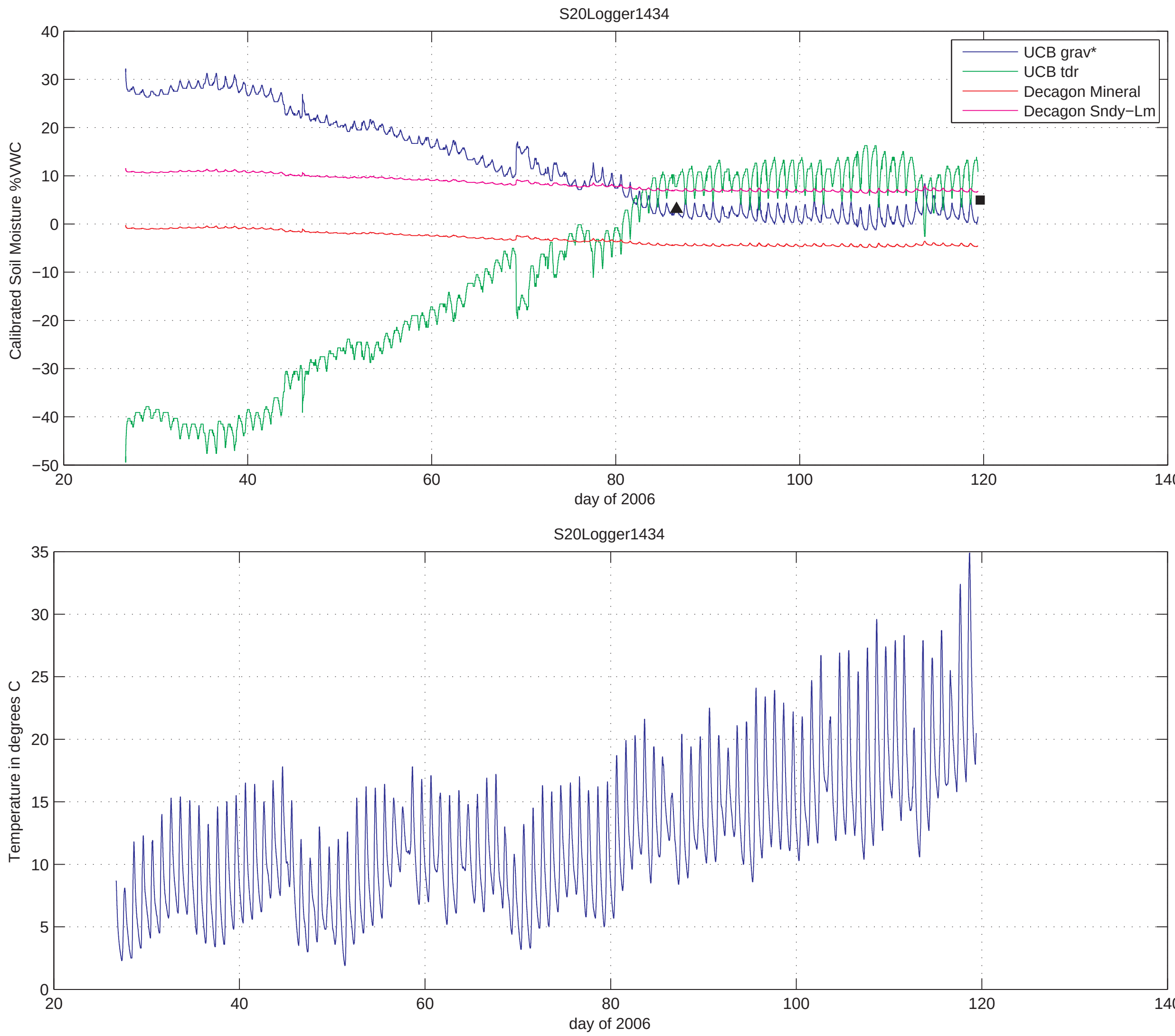

S20Logger1434
Calibrated Soil Moisture %VWC
day of 2006
UCB grav*
UCB tdr
Decagon Mineral
Decagon Sndy−Lm
S20Logger1434
Temperature in degrees C
day of 2006

Figure 26:

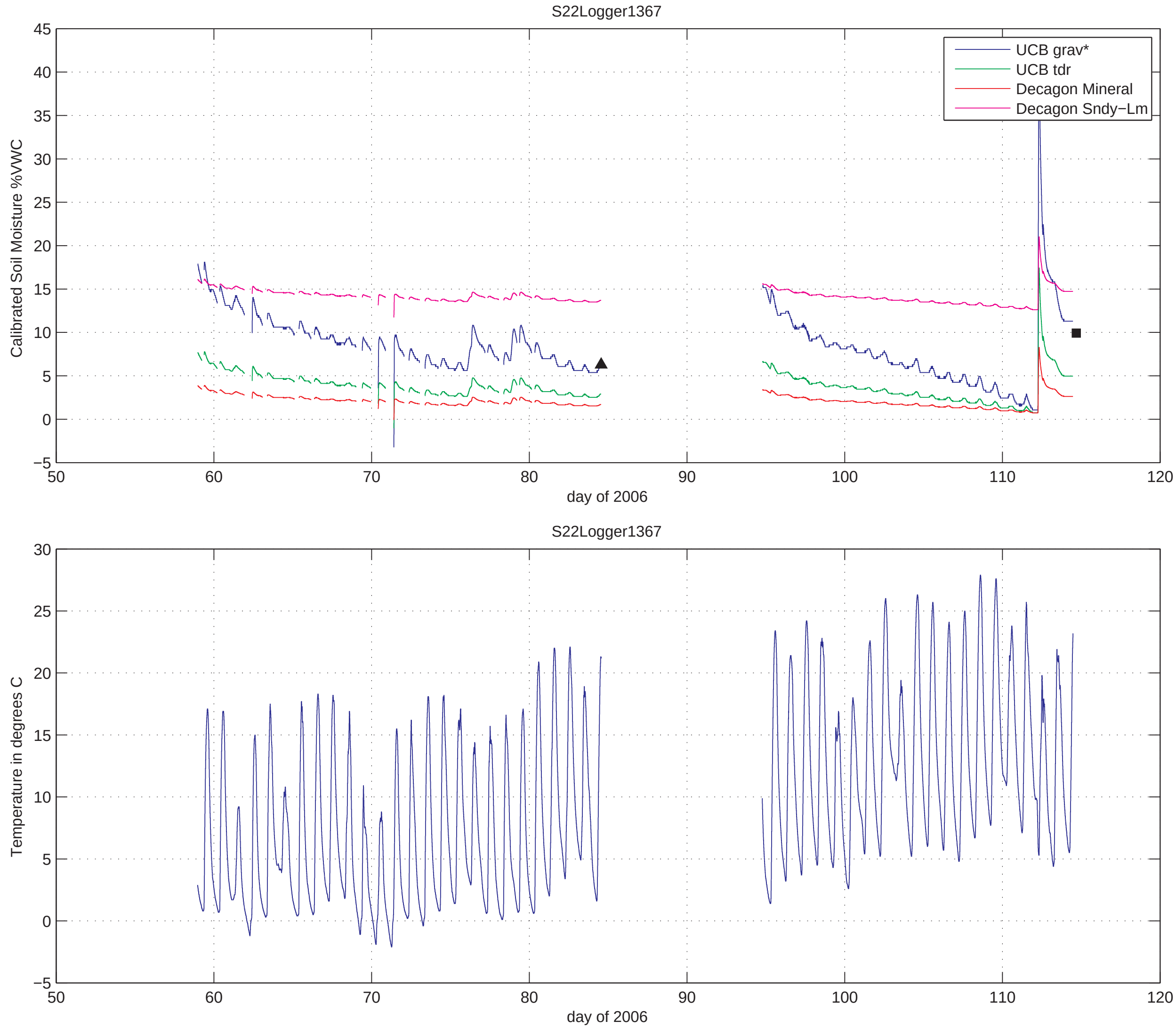
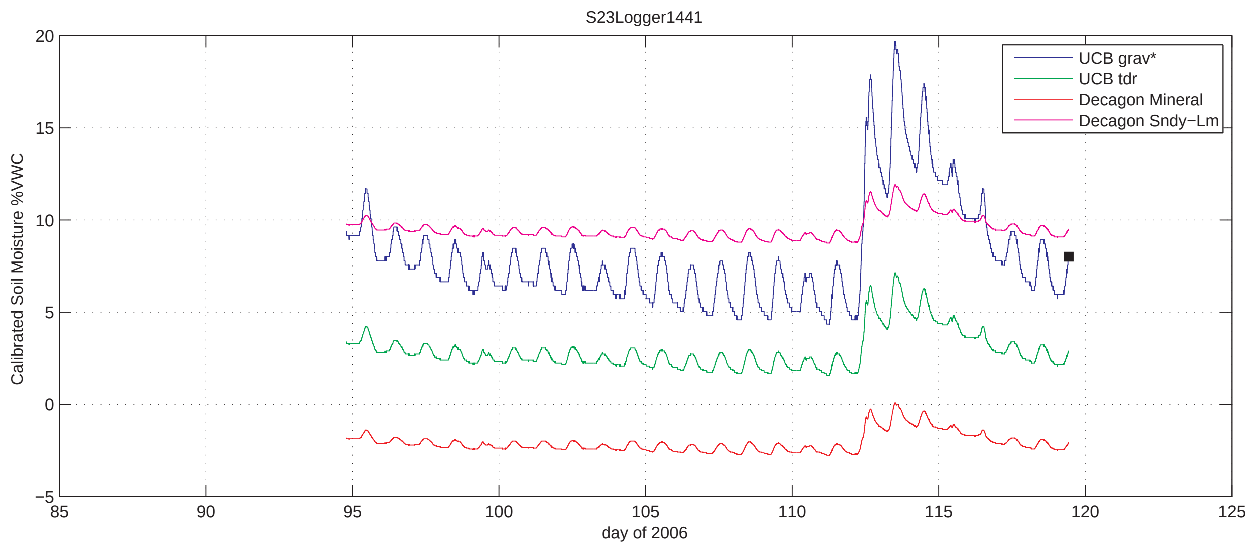


Figure 27: No data was recorded on the Logger 1367 between when we serviced the instruments on March 26, 2006 at 1 PM until April 5, 2006 at 6:34 PM. We believe the batteries were not working in the logger during that time.



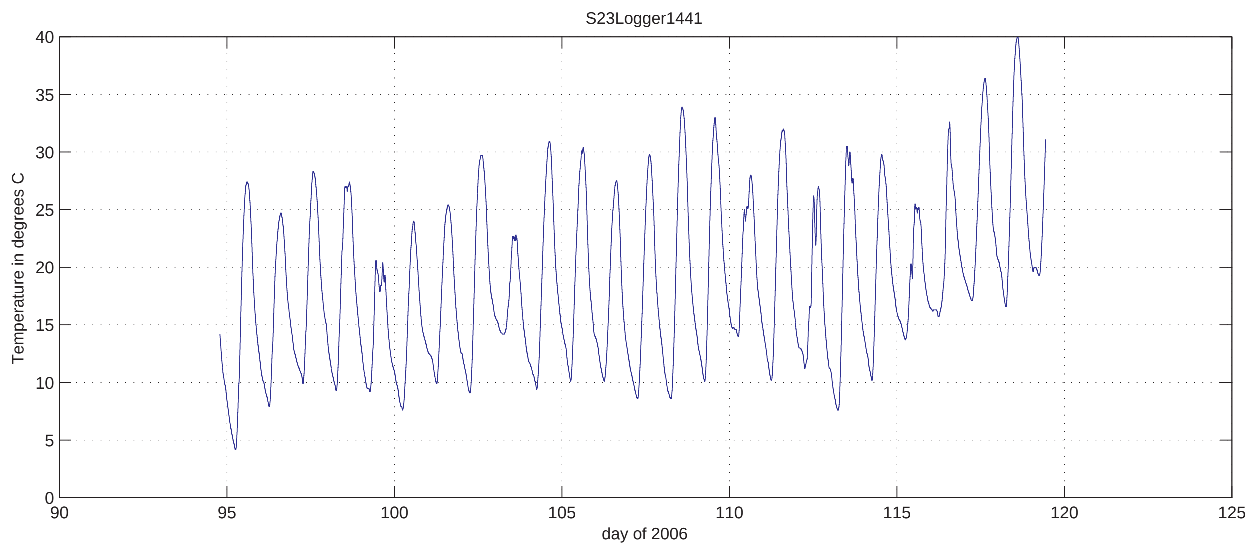


Figure 28: No data was recorded on Logger 1441 before April 5, 2006, probably due to battery problems.

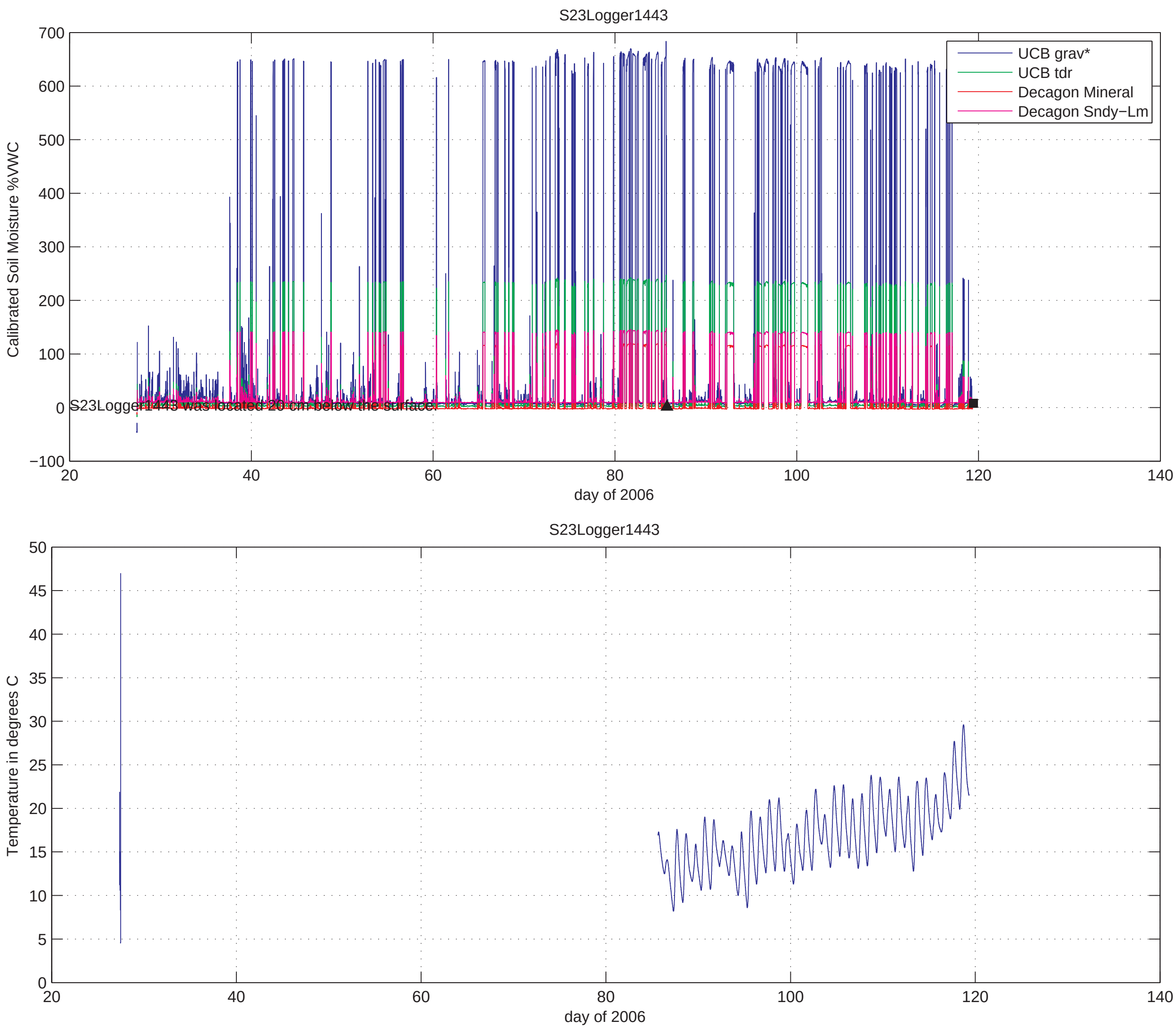


Figure 29: The data from this soil moisture sensor has not been included as part of the data set since it provided highly unreasonable values that were mostly out of range. Temperature data is missing for the first few months.

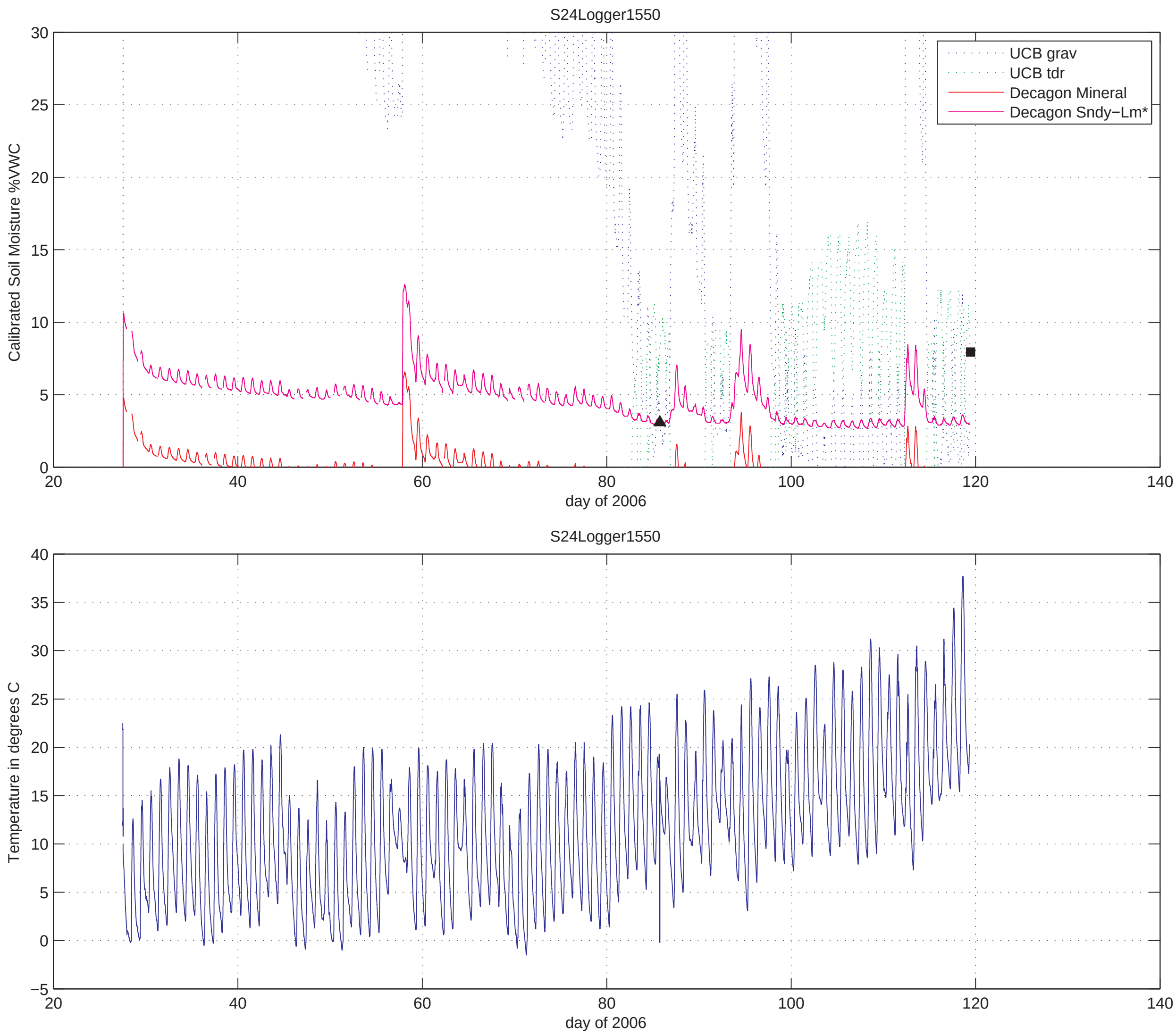
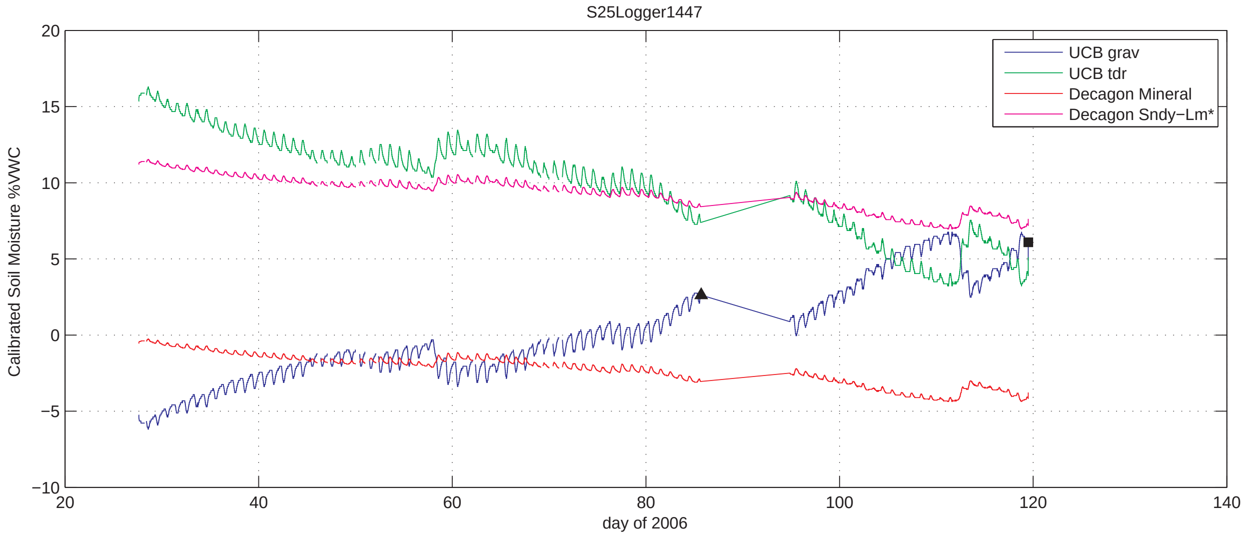


Figure 30: A Decagon Sandy Loam adjusted calibration was chosen because the soil type was determined to be sandy loam by touch test. We had most confidence in the first set of gravimetric measurements which differed by only 0.32 %VWC while the second set differed by 2.08 %VWC. In this case, we used the slope of Decagon's standard calibration curve and adjusted the y-intercept so that the calibration matches at the first gravimetric measurement. (Before this adjustment was made, the standard calibration curve yielded values about 7 %VWC higher on average than the adjusted curve shown above.)



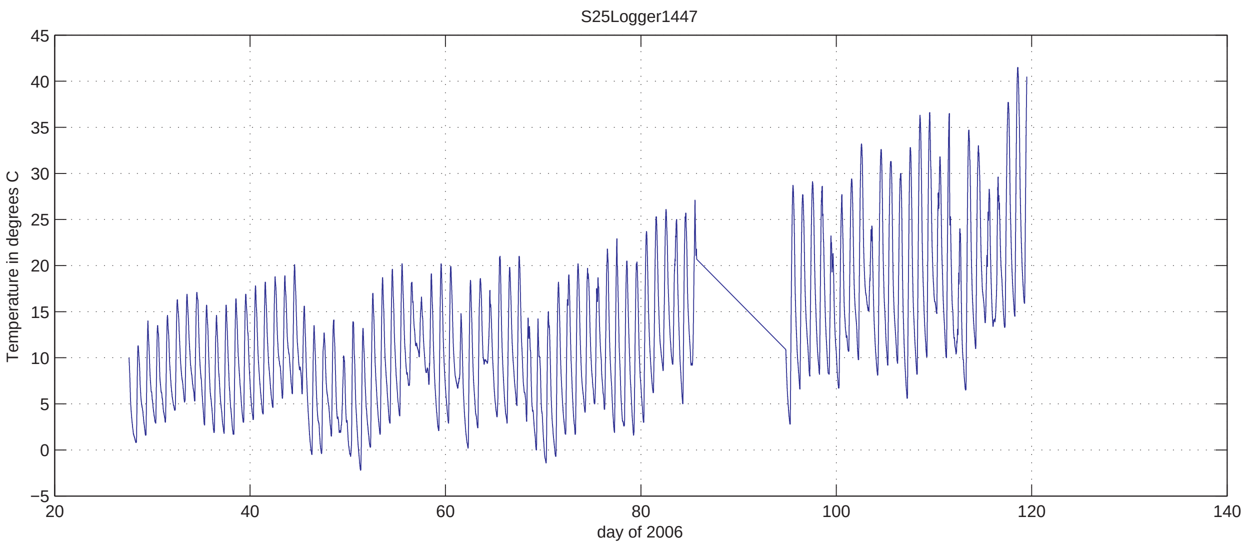


Figure 31: In two cases (S25 and S6), the gravimetric calibration yielded a slope opposite that of Decagon's standard mineral and sandy loam calibrations. This caused rain events to appear as periods of extreme drying instead of wetting, indicating that our gravimetric calibration was flawed for these sites. For S25, Decagon's sandy loam calibration was chosen because the mineral calibration produced negative soil moisture values (%VWC). No data was recorded on the Logger 1367 between when we serviced the instruments on March 27, 2006 at 5 PM until April 5, 2006 at 7:59 PM. We believe the batteries were not working in the logger during that time.

				“Gritty”			“Gritty and smooth”			“Smooth”				** Indicates multiple sensors at a site*
Site	***Logger***	**Sand**	**Loamy Sand**	**Sandy Loam**	**Sandy Clay Loam**	**Sandy Clay**	**Loam**	**Clay Loam**	**Clay**	**Silt Loam**	**Silty Clay Loam**	**Silty Clay**	**Organic**	***Date Sample Taken***
S1	1345	•												03/31/06 08:30 AM
S2	1332	•												03/28/06 04:09 PM
S3	1342												•	03/31/06 12:15 PM
S4	1445		•											03/28/06 12:00 PM
S5	1333												•	03/28/06 12:00 PM
S6	1446					•								03/26/06 11:00 AM
S8a*	1339		•											03/28/06 01:15 PM
S8b*	1334		•											03/31/06 10:00 AM
S8*	1440		•											03/28/06 02:30 PM
S9	1338			•										03/26/06 12:00 PM
S10	1548			•										03/27/06 04:30 PM
S11a*	1340			•										03/29/06 11:50 AM
S11b*	1430			•										03/26/06 01:20 PM
S11c*	1432			•										03/29/06 02:40 PM
S11d*	1439			•										03/26/06 11:00 AM
S12	1341							•						03/26/06 10:55 AM
S13	1435			•										03/28/06 02:45 PM
S14a*	1429			•										03/28/06 12:55 PM
S14b*	1549			•										03/26/06 10:50 AM
S15	1366				•									03/28/06 12:00 PM
S16	1551					•								03/27/06 03:10 PM
S17	1442		•											03/31/06 02:00 PM
S18	1343			•										03/27/06 05:35 PM
S19	1344												•	03/28/06 03:35 PM
S20	1434		•											03/28/06 12:15 PM
S22	1367		•											03/27/06 05:00 PM
S23*	1441				•									03/28/06 01:30 PM
S23*	1443				•									03/29/06 02:35 PM
S24	1550			•										03/27/06 06:10 PM
S25	1447				•									03/29/06 12:50 PM

		Sensor Depth	Calibration Curve			
Site	***Logger***	[cm]	*UCB Gravimetric*	*UCB TDR*	*Decagon Mineral*	*Decagon Sandy Loam*
S1	1345	5	X			
S2	1332	5	X			
S3	1342	5	X			
S4	1445	5	X			
S5	1333	5			X	
S6	1446	5			X	
S8a*	1339	5	X			
S8b*	1334	5	X			
S8*	1440	20	X			
S9	1338	5	X			
S10	1548	5	X			
S11a*	1340	5	X			
S11b*	1430	5	X			
S11c*	1432	30	X			
S11d*	1439	50	X			
S12	1341	5			X	
S13	1435	5	X			
S14a*	1429	5	X			
S14b*	1549	20	X			
S15	1366	5	X			
S16	1551	5	X			
S17	1442	5	X			
S18	1343	5	X			
S19	1344	5				X
S20	1434	5	X			
S22	1367	5	X			
S23*	1441	5	X			
S23*	1443	20	NA	NA	NA	NA
S24	1550	5				X
S25	1447	5				X

Site	Logger	Elevation (ft)	Latitude (degrees, minutes)		Longitude (degrees, minutes)		Latitude (degrees)	Longitude (degrees)
S1	1345	3971	37	14.000	118	17.266	37.233	118.288
S2	1332	6360	36	56.901	118	19.561	36.948	118.326
S3	1342	3835	36	57.576	118	13.843	36.960	118.231
S4	1445	3900	36	52.477	118	14.480	36.875	118.241
S5	1333	3834	36	53.219	118	14.191	36.887	118.237
S6	1446	6643	36	55.109	118	6.631	36.918	118.111
S8a*	1339	6766	36	47.411	118	18.063	36.790	118.301
S8b*	1334							
S8*	1440							
S9	1338	5697	36	46.098	118	16.566	36.768	118.276
S10	1348	4842	36	46.668	118	14.598	36.778	118.243
S11a*	1340	4180	36	47.184	118	12.468	36.786	118.208
S11b*	1430							
S11c*	1432							
S11d*	1439							
S12	1341	3770	36	48.043	118	7.970	36.801	118.133
S13	1435	3856	36	48.766	118	6.523	36.813	118.109
S14a*	1429	4870	36	50.662	118	5.116	36.844	118.085
S14b*	1549							
S15	1366	7003	36	51.663	118	3.571	36.861	118.060
S16	1551	7448	36	51.824	118	3.190	36.864	118.053
S17	1442	5953	36	41.889	118	14.778	36.698	118.246
S18	1343	4744	36	43.158	118	12.254	36.719	118.204
S19	1344	3836	36	43.930	118	8.821	36.732	118.147
S20	1434	4087	36	45.106	118	3.176	36.752	118.053
S22	1367	5603	36	35.672	118	10.333	36.595	118.172
S23*	1441	3862	36	36.398	118	4.600	36.607	118.077
S23*	1443							
S24	1550	3691	36	37.171	118	2.053	36.620	118.034
S25	1447	4236	36	38.405	117	59.763	36.640	117.996

* Indicates multiple sensors at a site