4 RESULTS AND ANALYSIS

4.1 Thermal performance

In this study, the ability of a green roof to lower the cooling demands of a building is of interest; and is measured indirectly as its ability to reduce the average temperature (T_{ave}) incident on a roof, as well as its ability to reduce the amplitude (A) of daily temperature fluctuations incident on a roof. The location of the thermocouples and soil water sensors used to monitor the thermal performance of the green roof setup as a function of volumetric water content (VWC) are indicated in Figure 3-1.

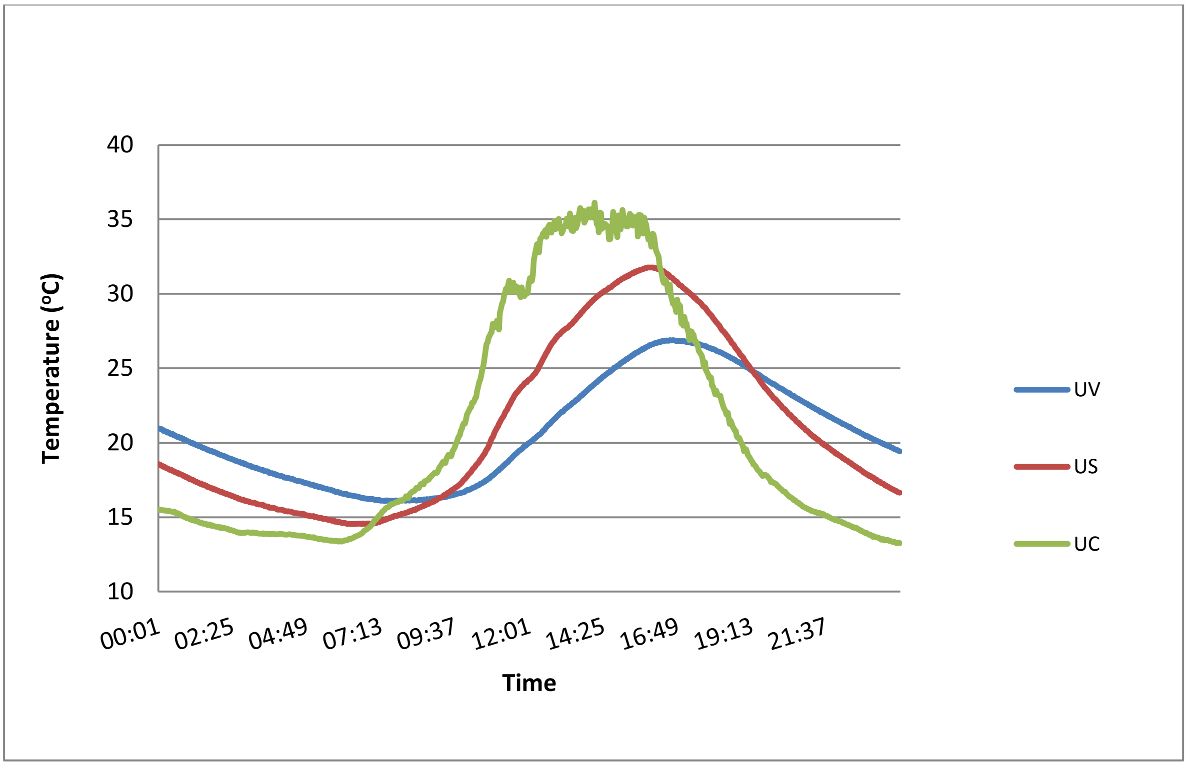

Figure 4-1: Temperature data for the green roof setup on a typical summer day. The abbreviations in the legend are defined in Figure 3-1.

Figure 4-1 shows temperature data for the green roof setup on a typical summer day. The green roof consistently lowers T_{ave} and A, and slightly delays the timing of temperature peaks. T_{ave} is simply taken as the average temperature over a 24 hour period, and A is taken as the difference between the maximum and minimum temperatures over the 24 hour period.

In this instance (Figure 4-1) the peak temperature under the conventional roof tiles was 36 ^{o}C, whilst those for bare soil (US) and vegetation (UV) were 32 ^{o}C and 27 ^{o}C, respectively. The green roof significantly lowers the peak roof temperature as indicated by the temperature difference of 9 ^{o}C between the normal roof and the vegetated green roof.

According to Figure 1-5, the factors affecting the thermal performance of green roofs include shading, evapotranspiration and insulation effects of the soil and vegetation. In order to gain a better understanding of the role of the various processes in this study a series of vertical temperature profiles for the vegetated (Box 1) and non-vegetated (Box 2) green roofs throughout a typical summer day was plotted (Figure 4-7 to Figure 4-13). Here, the same day was chosen as in Figure 4-1. Figure 4-2 shows the soil surface temperatures throughout the day (0.00 m in figure 3-2). Box 1 and Box 2 have very similar surface temperatures throughout the day, indicating that shading has a minimal effect.

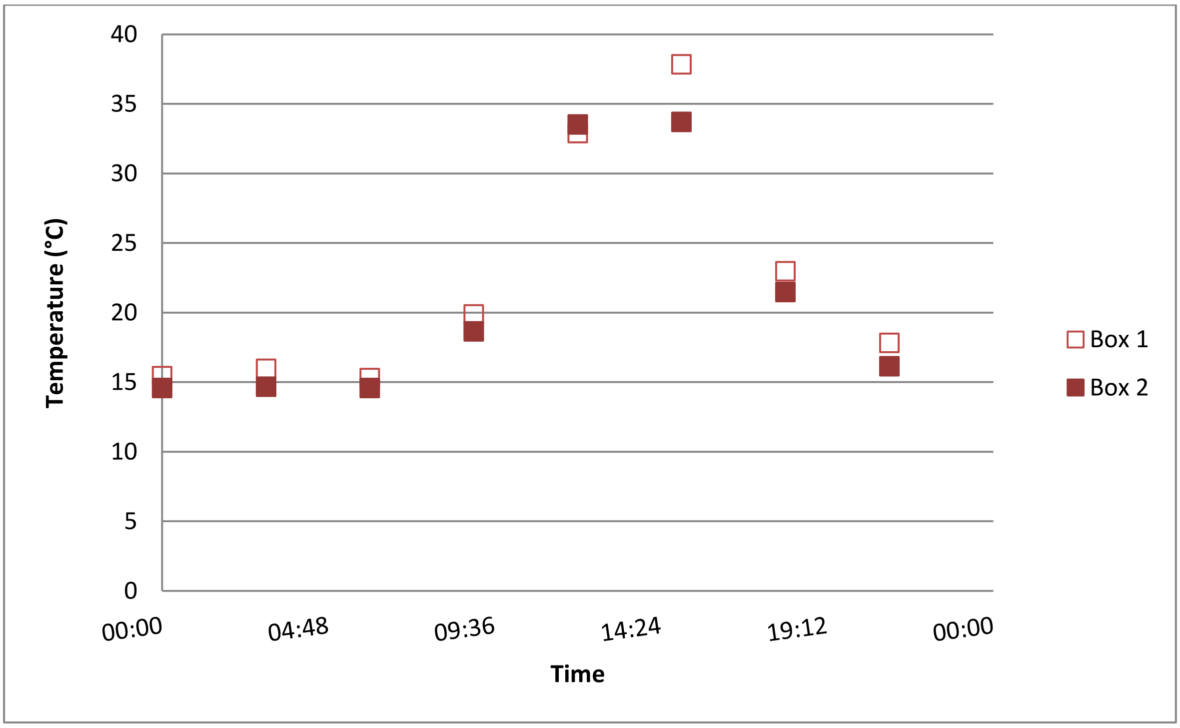

Figure 4-2: Soil surface temperatures throughout the day (0.00 m in Figure 3-1). Box 1 and Box 2 are defined in Figure 3-1.

Figure 4-3 and Figure 4-4 show the vertical temperature gradients in Box 1 and Box 2 throughout the day. Two gradients were plotted: ‘A’ between 0.00 m and 0.02 m, and ‘B’ between 0.02 m and 0.08 m. ‘A’ indicates the flow of energy into and out of the soil body, while ‘B’ indicates the flow of energy within the soil. This reasoning is based on Fourier’s law. When there is a temperature gradient within a body, heat energy flows from the region of high temperature to the region of low temperature. This is known as conduction heat transfer, and is described by Fourier's Law (Serway, 1996):

$$\frac{Q}{\Delta t} = -k_q A \frac{\Delta T}{\Delta x} \qquad \text{Equation 4-1}$$

where Q is the thermal energy transferred in a time Δt and $Q/\Delta t$ represents the rate at which heat flows. $Q/\Delta t$ is proportional to the cross sectional area (A) and the temperature gradient ($\Delta T/\Delta x$). The proportionality constant (k_q) symbolises the thermal conductivity of the material. The minus sign is to show that the flow of heat is from hotter to colder regions.

Taking into account experimental variation, it can be argued that at night Box 1 and Box 2 show similar temperature gradients, while during the day, Box 1 has a significantly higher surface temperature gradient. Box 1 also has a more uniform temperature profile than Box 2. Both of these observations point towards the influence of evapotranspiration playing a major role, with similar insulation effects from both boxes at the same VWC. This is further supported by looking at the VWC for the two boxes over the day (Figure 4-5). The VWC in the vegetated boxes drops throughout the day, indicating evaporative losses.

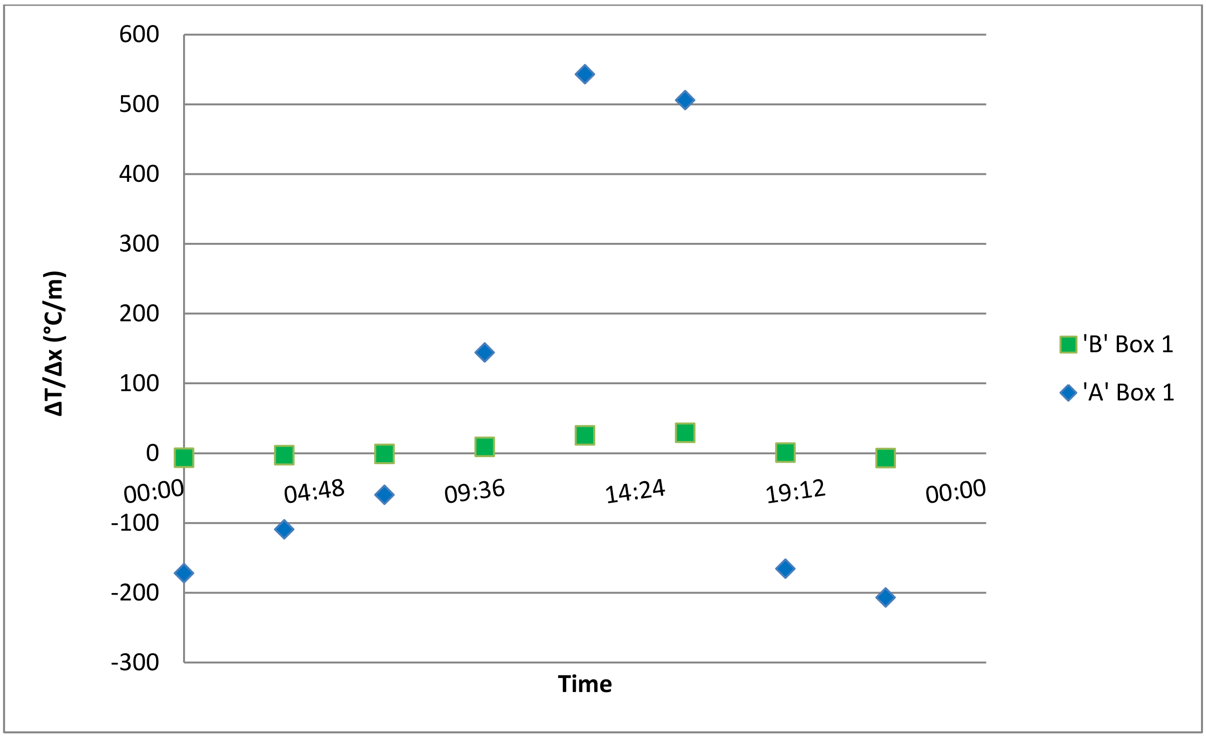

Figure 4-3: Vertical temperature gradients in Box 1 throughout the day. Two gradients are plotted: A between 0.00m and 0.02 m, and B between 0.02m and 0.08 m. Box 1 is defined in Figure 3-1.

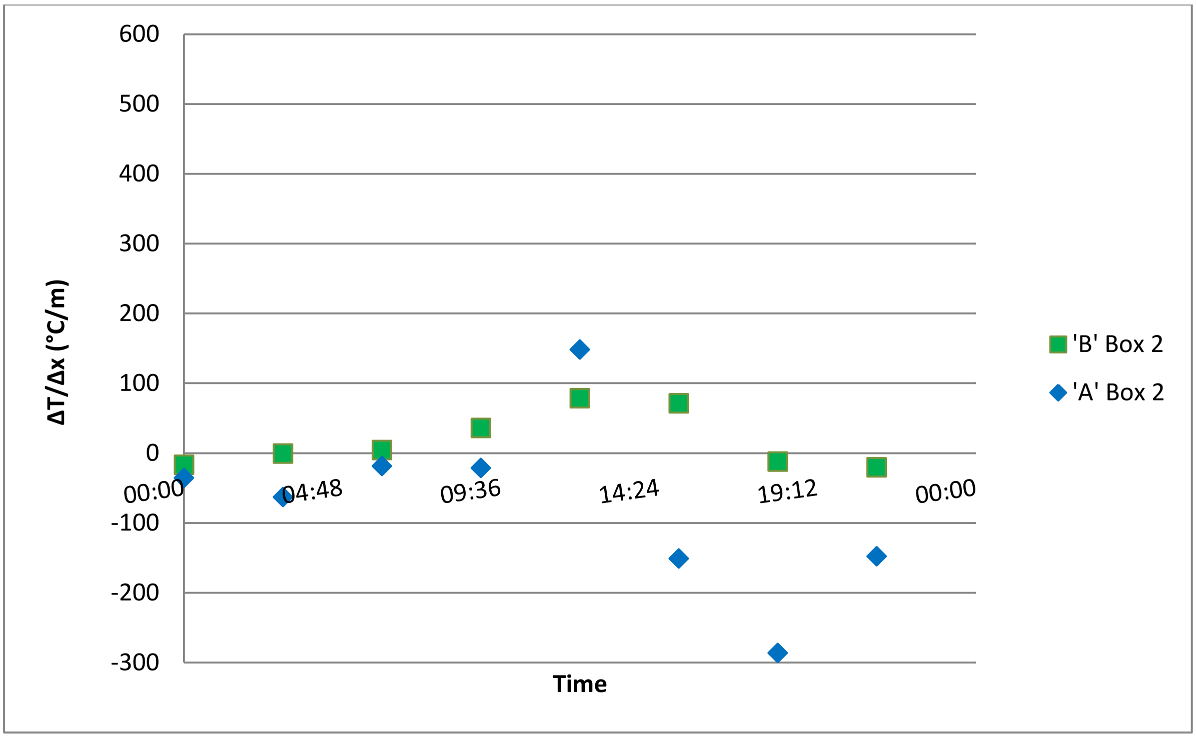

Figure 4-4: Vertical temperature gradient in Box 2 throughout the day. Two gradients were plotted: A between 0.00m and 0.02 m, and B between 0.02m and 0.08 m. Box 2 is defined in Figure 3-1.

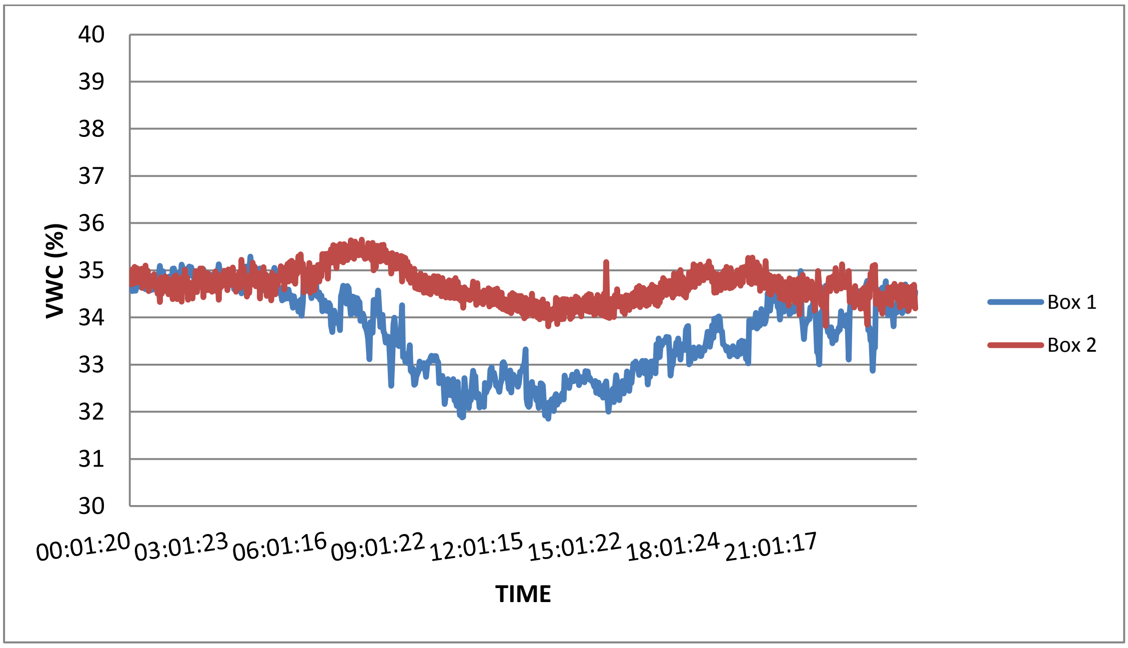

Figure 4-5: VWC for the typical summer day presented in Figure 4-1. The legend is defined in Figure 3-1.

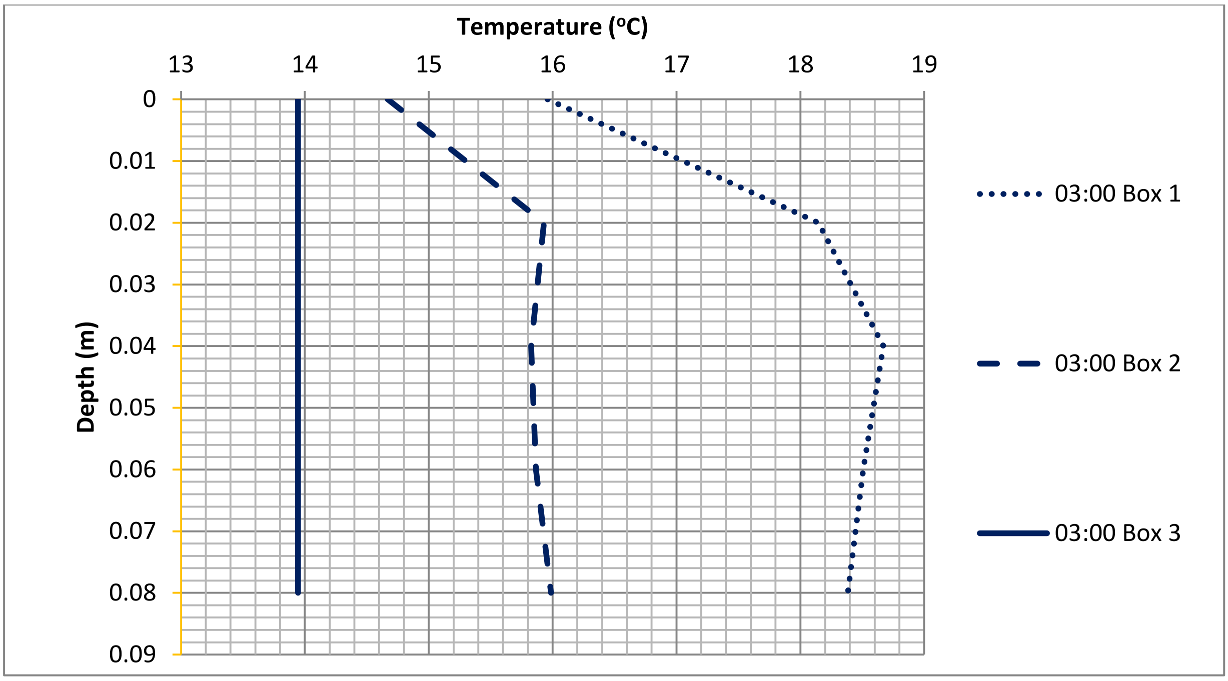

Figure 4-6: Vertical temperature profile taken at 03:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

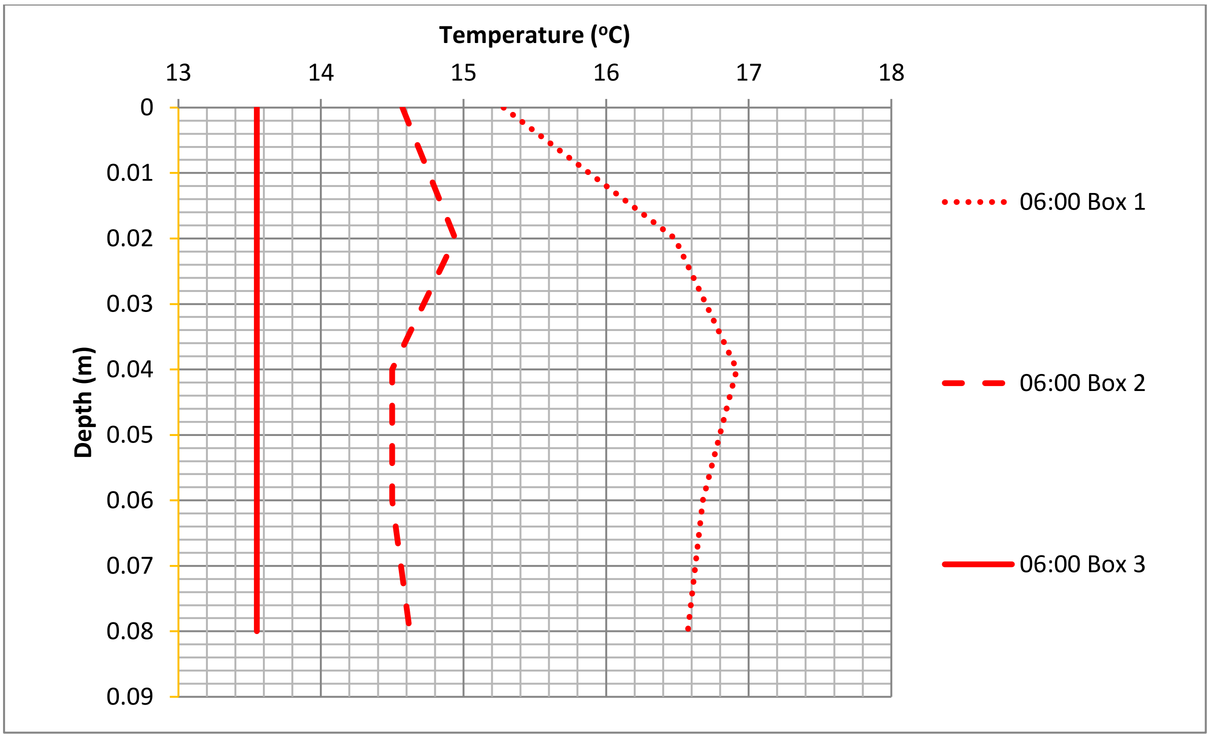

Figure 4-7: Vertical temperature profile taken at 06:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

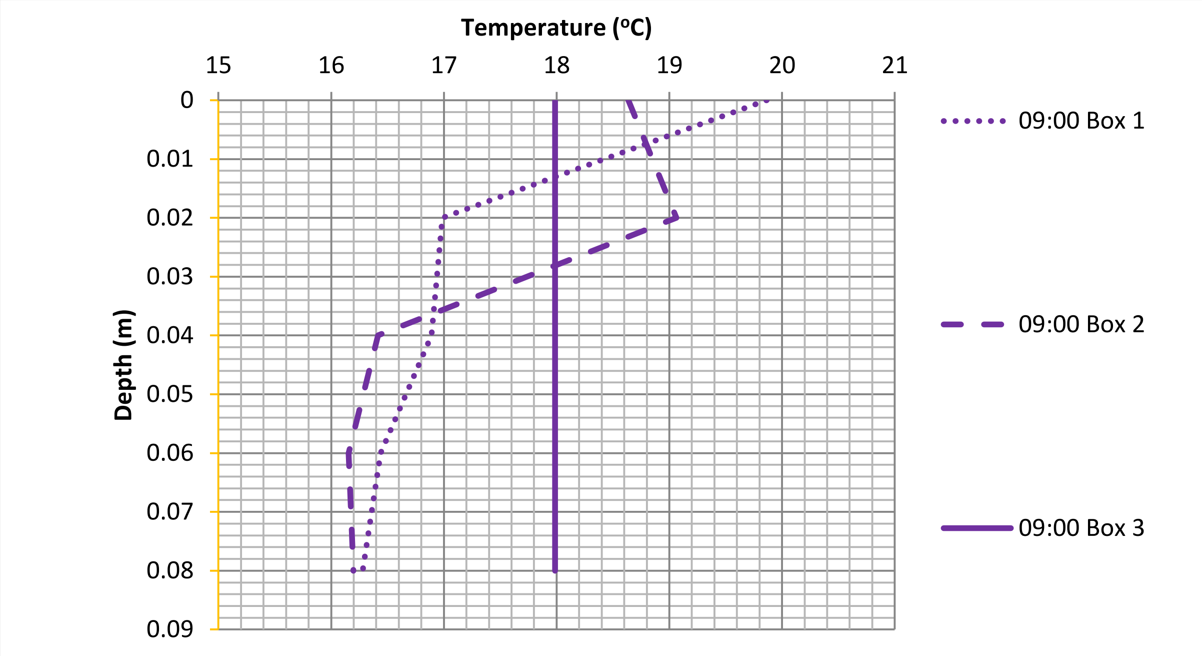

Figure 4-8: Vertical temperature profile taken at 09:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

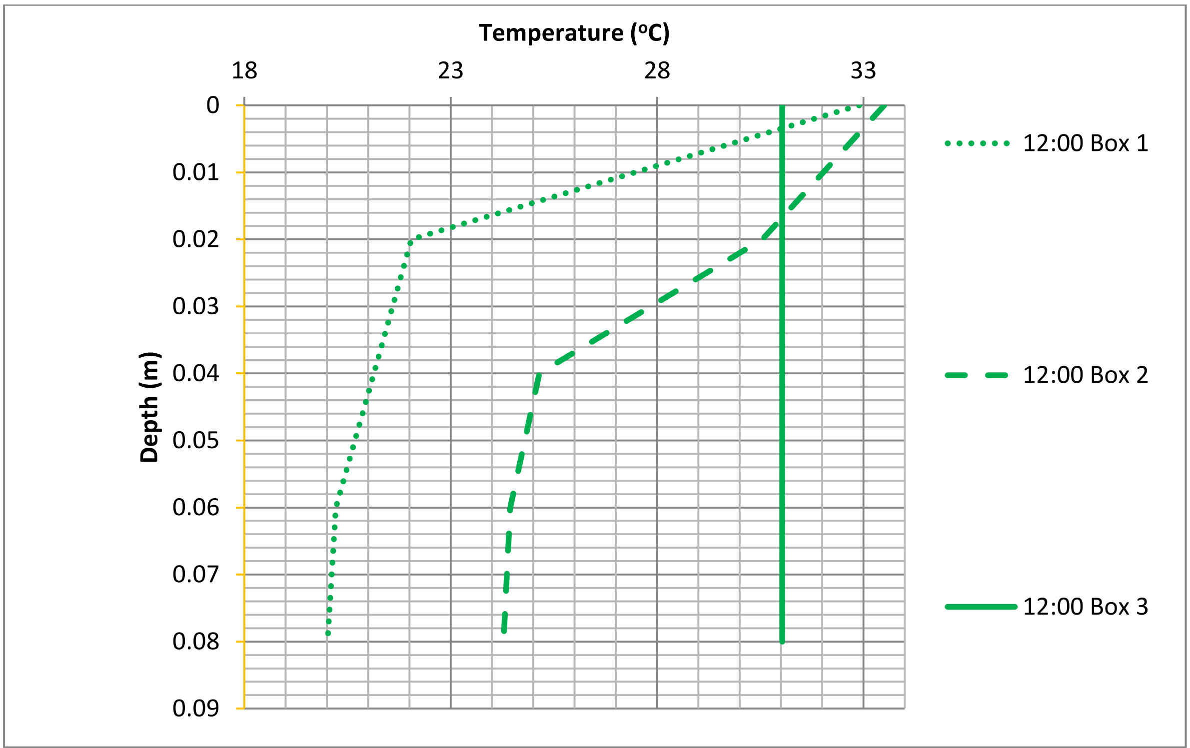

Figure 4-9: Vertical temperature profile taken at 12:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

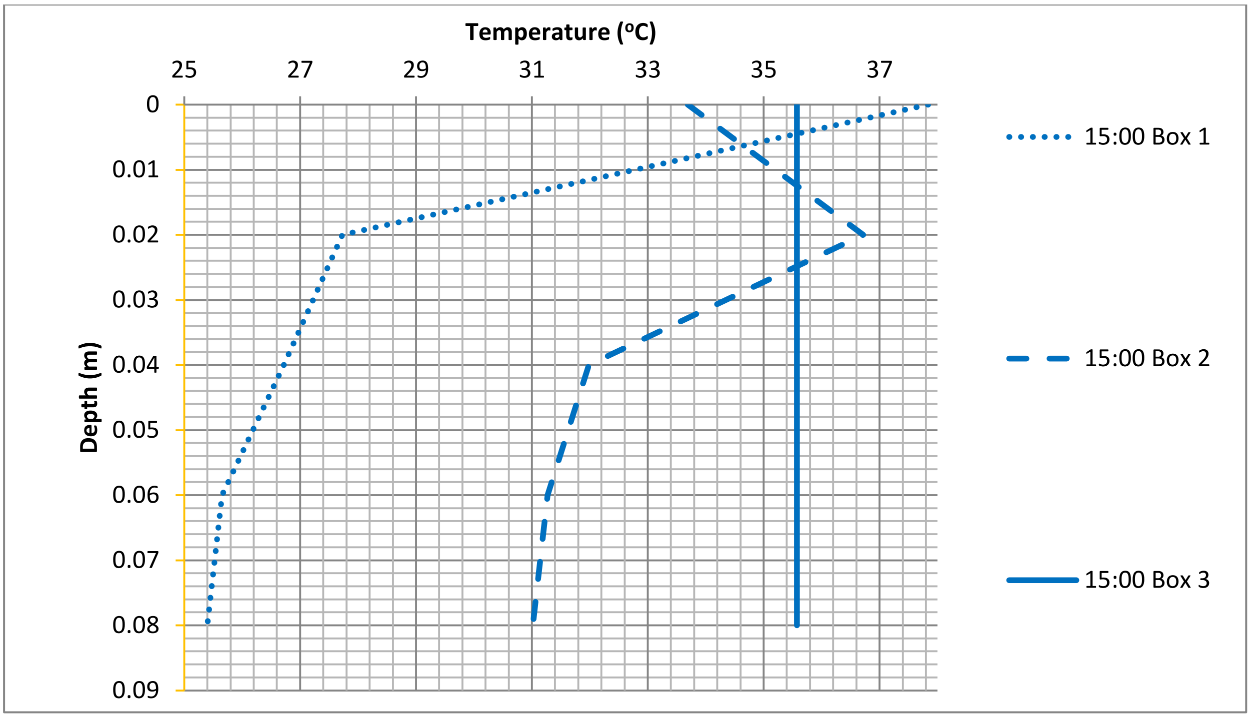

Figure 4-10: Vertical temperature profile taken at 15:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

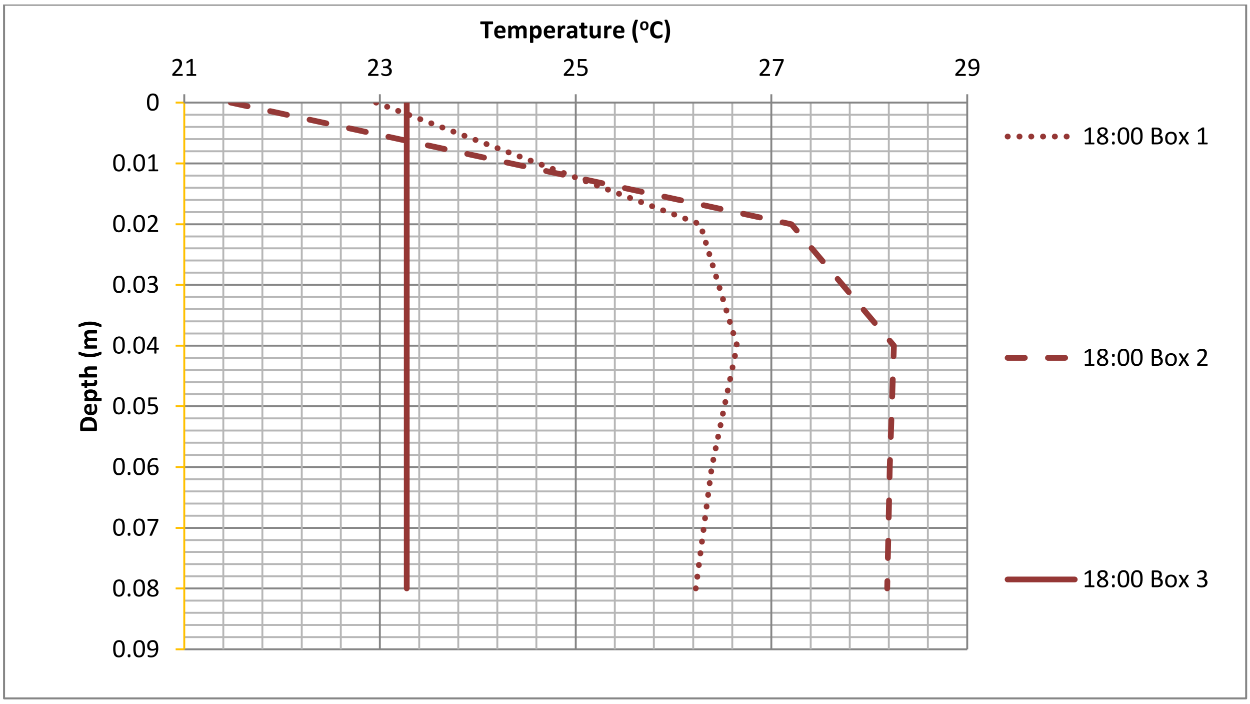

Figure 4-11: Vertical temperature profile taken at 18:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

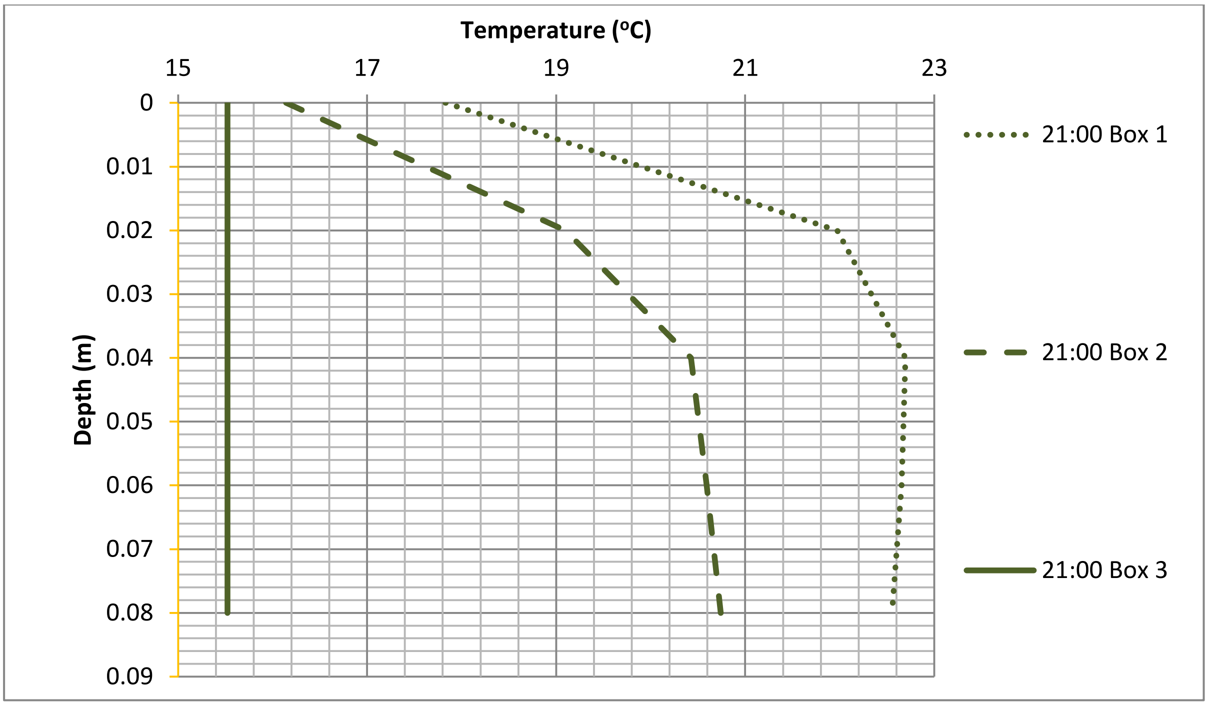

Figure 4-12: Vertical temperature profile taken at 21:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

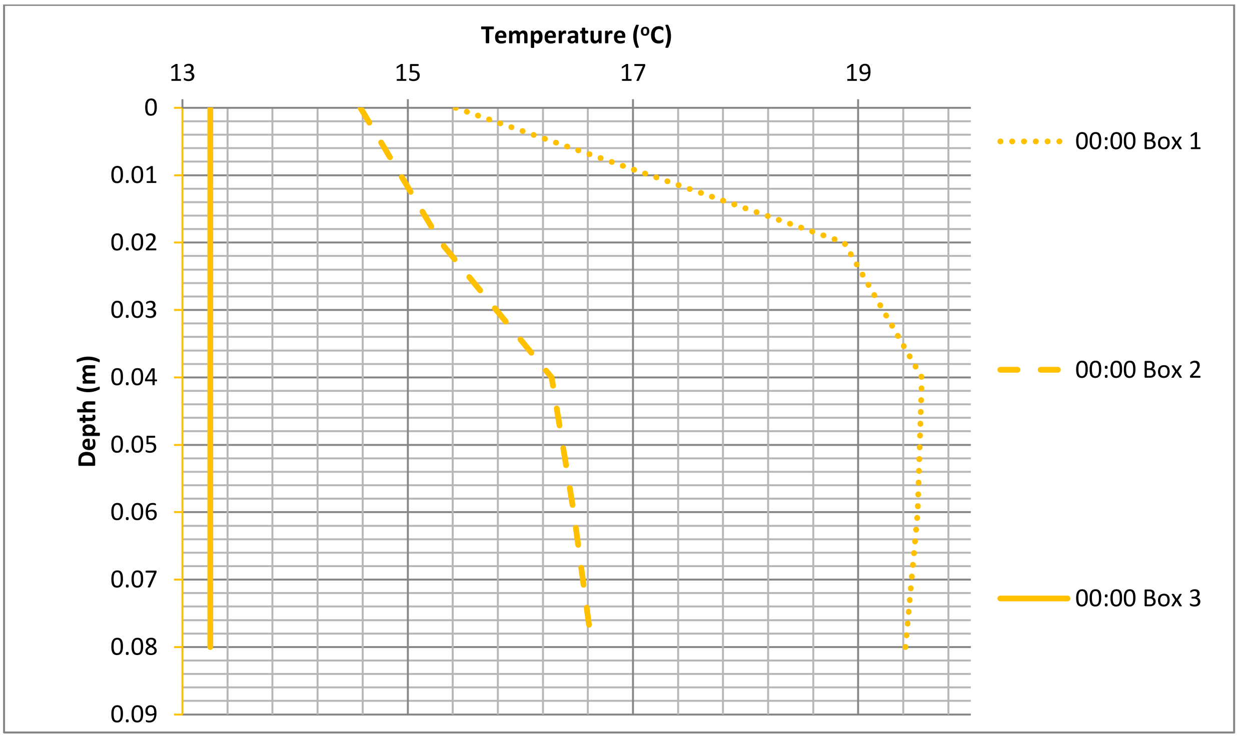

Figure 4-13: Vertical temperature profile taken at 00:00 for a typical summer day. The locations of the thermocouples are indicated in Figure 3-1. The temperature profile for the control box was artificially set to the temperature under the control box (UC in Figure 3-1), and used as a reference.

4.2 Effect of VWC on thermal performance

4.2.1 Source data

In order to determine the effect of VWC on A and T_{ave}, data from 5 days in the months of December 2011 and January 2012 were used. These days were chosen in such a way that all 5 days experienced similar average outdoor temperatures, and amplitudes in outdoor temperature variations (outdoor temperatures were based on thermocouple UC –Figure 3-2); and that each day had a different average VWC. The idea was to vary SWC while keeping outdoor temperatures constant. In this way, the effect of VWC on thermal performance could be isolated. It was also taken into account that VWC should ideally be constant over any particular 24 hour period to ensure consistency in results. The thermal performance data for each day are tabulated in Table 4-1.

Table 4-1: Thermal performance data used in this analysis. The location of the thermocouples and soil water sensors used in this study are indicated in Figure 3-1.

Day	ρ_β (kg.m^{-3})		VWC (%)		C_v (J.m^{-3}.^{o}C^{-1})		D_q (m^2.s^{-1})		K_q (J.s^{-1}.m^{-1}. ^{o}C^{-1})		T_{ave} (^{o}C)					A (^{o}C)		
	Box 1	Box 2	Box 1	Box 2	Box 1	Box 2	Box 1	Box 2	Box 1	Box 2	Box 1 UV	Box 2 US	Box 3 UC	Box 1 UCV	Box 2 TS	Box 1	Box 2	Box 3
1(7Jan)	1220	1222	36.8	37.1	2.58	2.62	0.0271	0.33056	3.01	23.13	23.2	23.0	23.9	24.5	23.9	17.3	26.1	35.3
2(27Jan)	1210	1210	37.7	37.6	2.61	2.58	0.5889	0.5889	41.02	40.51	24.1	22.3	25.2	23.8	25.1	15.9	25.1	35.3
3(25Dec)	1220	1220	36.9	36.5	2.57	2.55	0.0158	0.0103	1.08	0.71	22.2	20.5	25.8	21.6	22.6	13.6	20.4	34.4
4(2Jan)	1220	1220	47.5	36.2	3.01	2.54	0.0164	0.0226	1.32	1.52	23.5	21.6	25.9	21.7	24.6	11.7	23.2	33.8
5(3Jan)	1220	1220	39.7	35.7	2.68	2.52	0.0132	0.0226	0.95	1.51	26.1	23.3	26.3	23.9	26.9	16.1	26.9	34.4

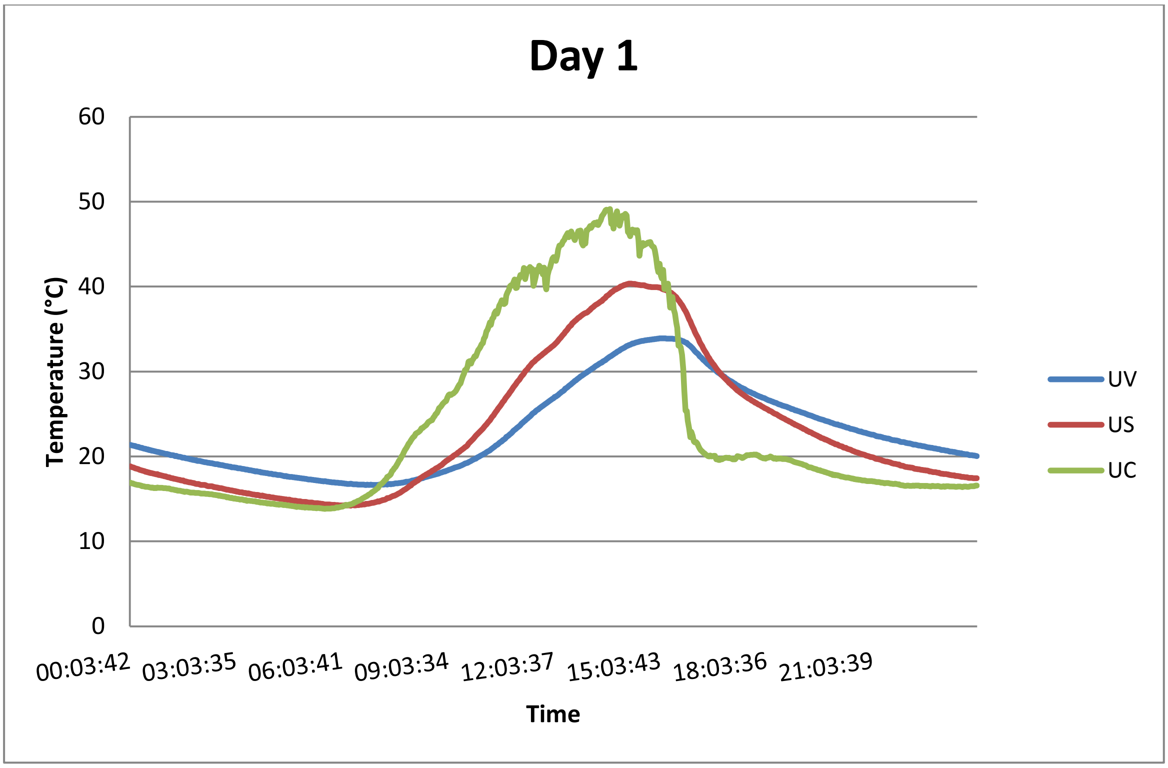

Figure 4-14: Temperature data for Day 1. The abbreviations in the legend are defined in Figure 3-1.

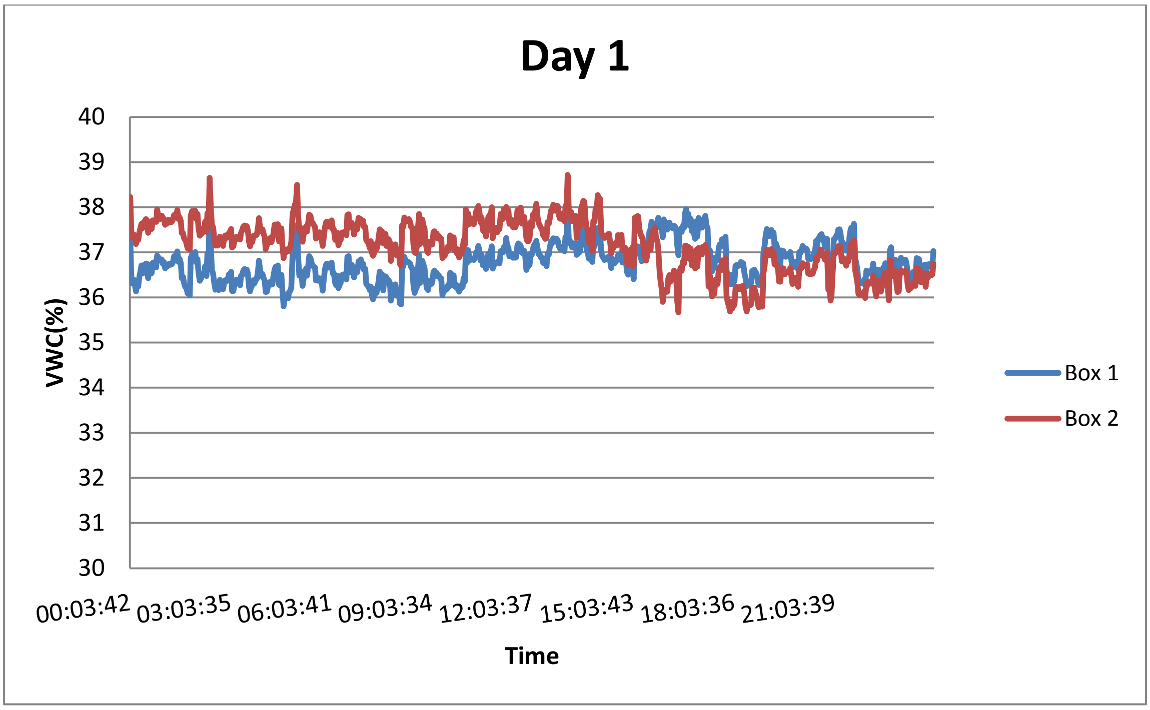

Figure 4-15: VWC for Day 1. Box 1 and Box 2 are defined in Figure 3-1.

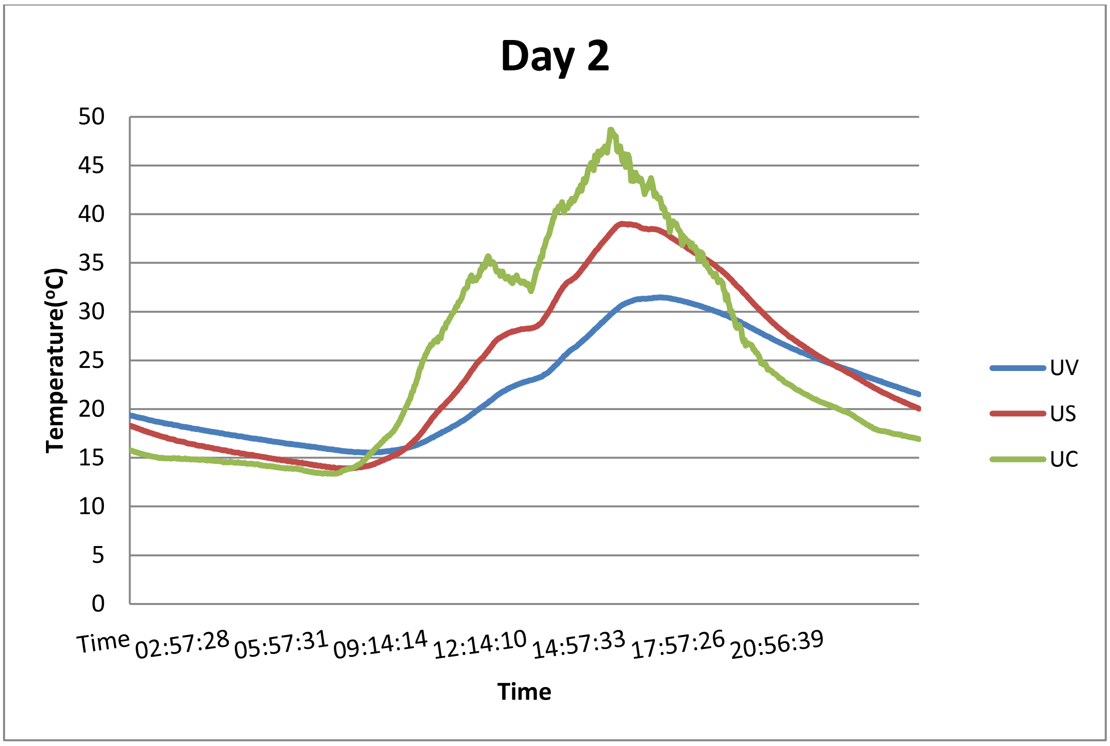

Figure 4-16: Temperature data for Day 2. The abbreviations in the legend are defined in Figure 3-1.

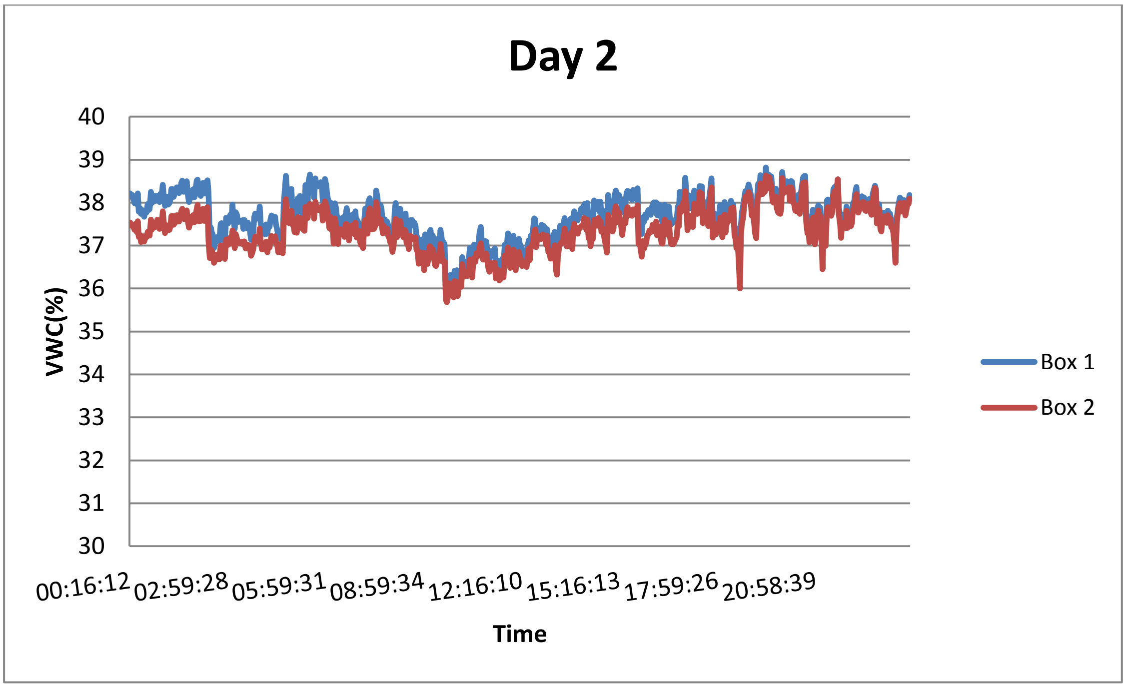

Figure 4-17: VWC for Day 2. Box 1 and Box 2 are defined in Figure 3-1.

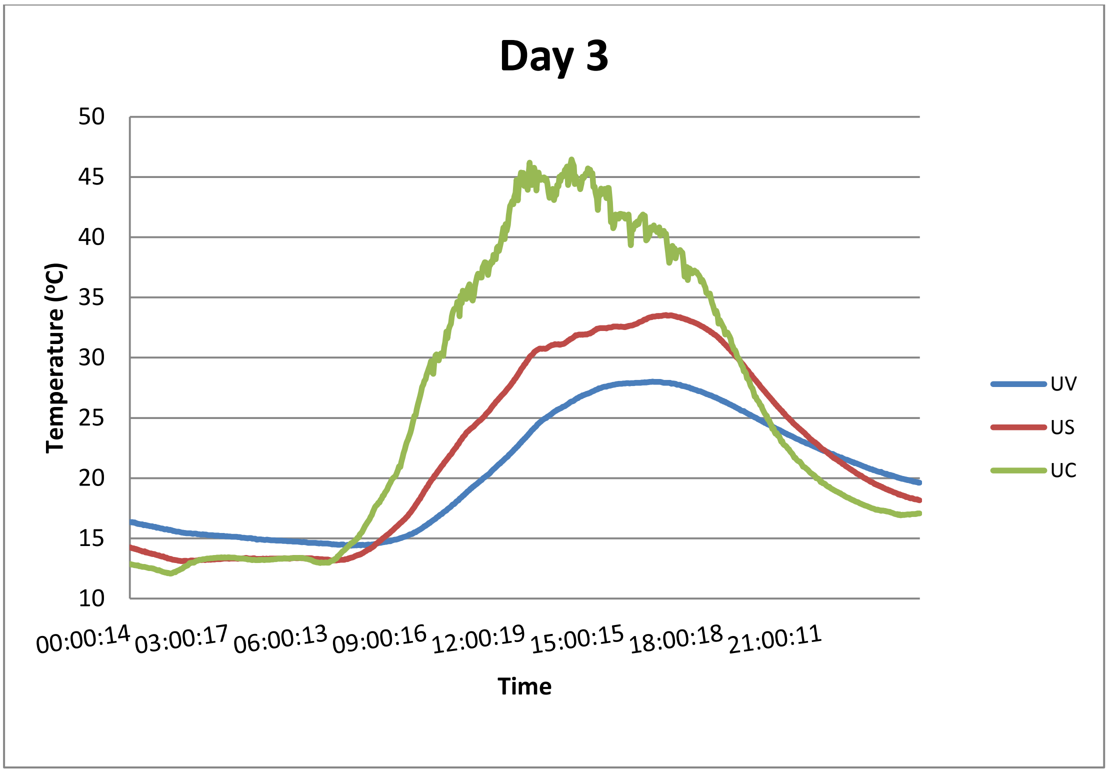

Figure 4-18: Temperature data for Day 3. The abbreviations in the legend are defined in Figure 3-1.

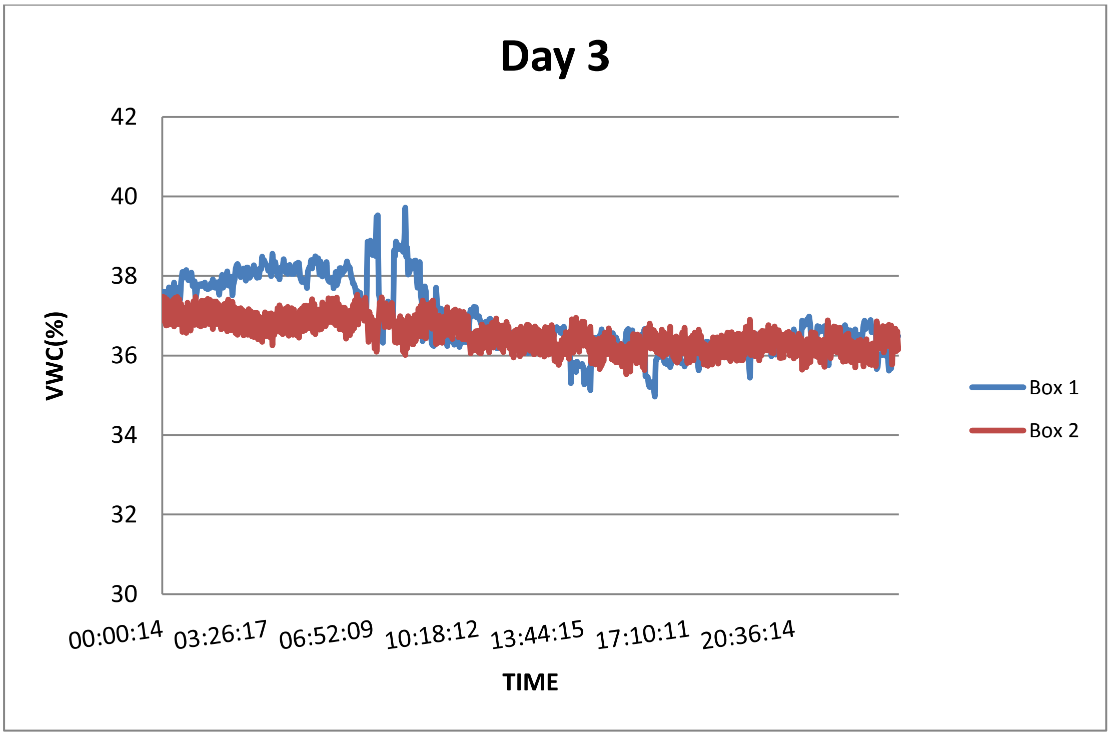

Figure 4-19: VWC for Day 3. Box 1 and Box 2 are defined in Figure 3-1.

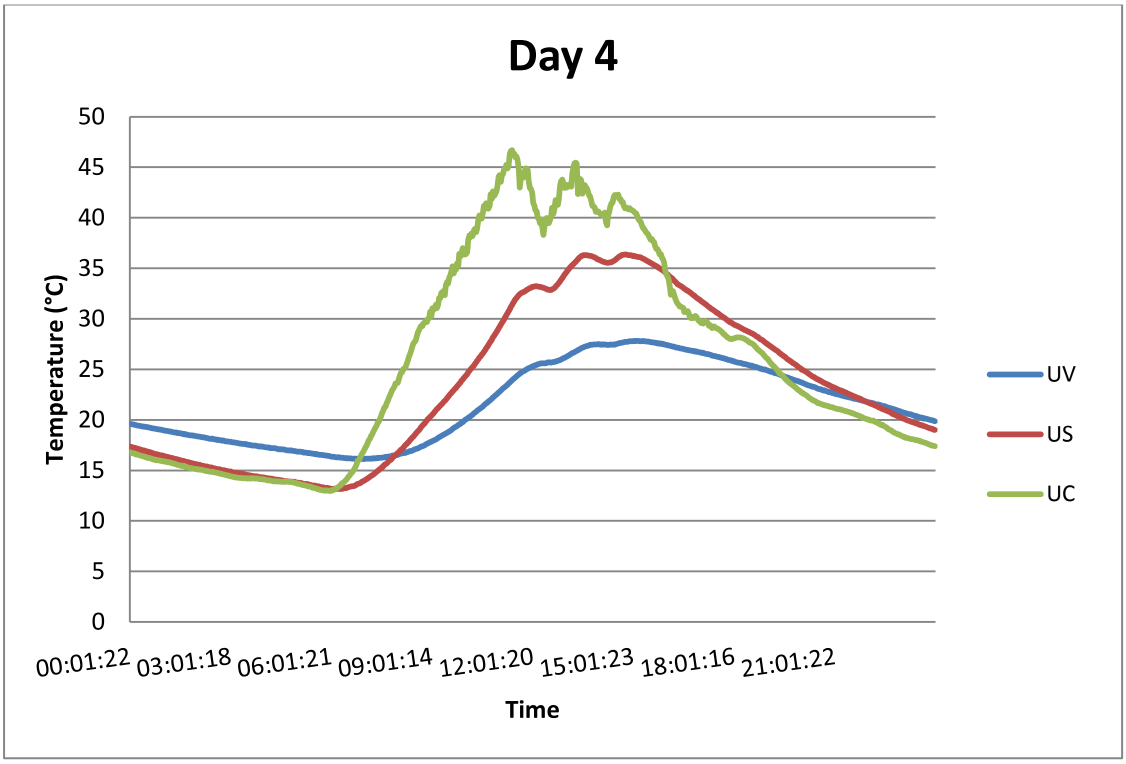

Figure 4-20: Temperature data for Day 4. The abbreviations in the legend are defined in Figure 3-1.

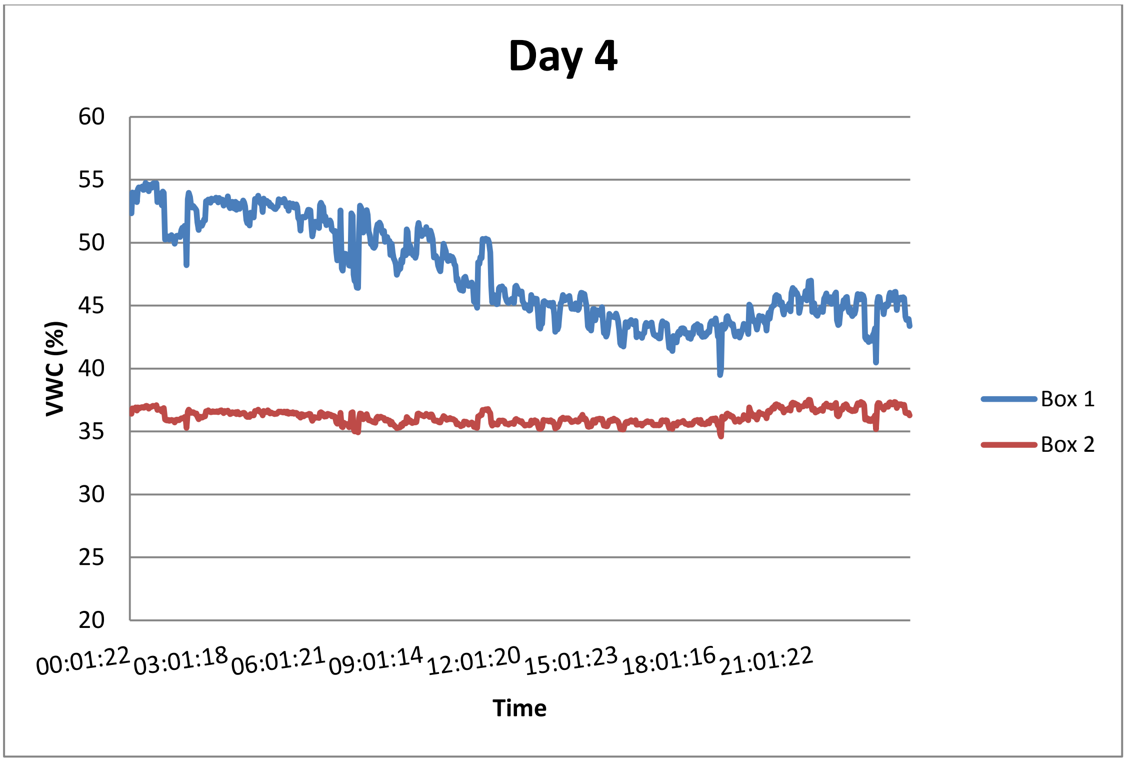

Figure 4-21: VWC for Day 4. Box 1 and Box 2 are defined in Figure 3-1.

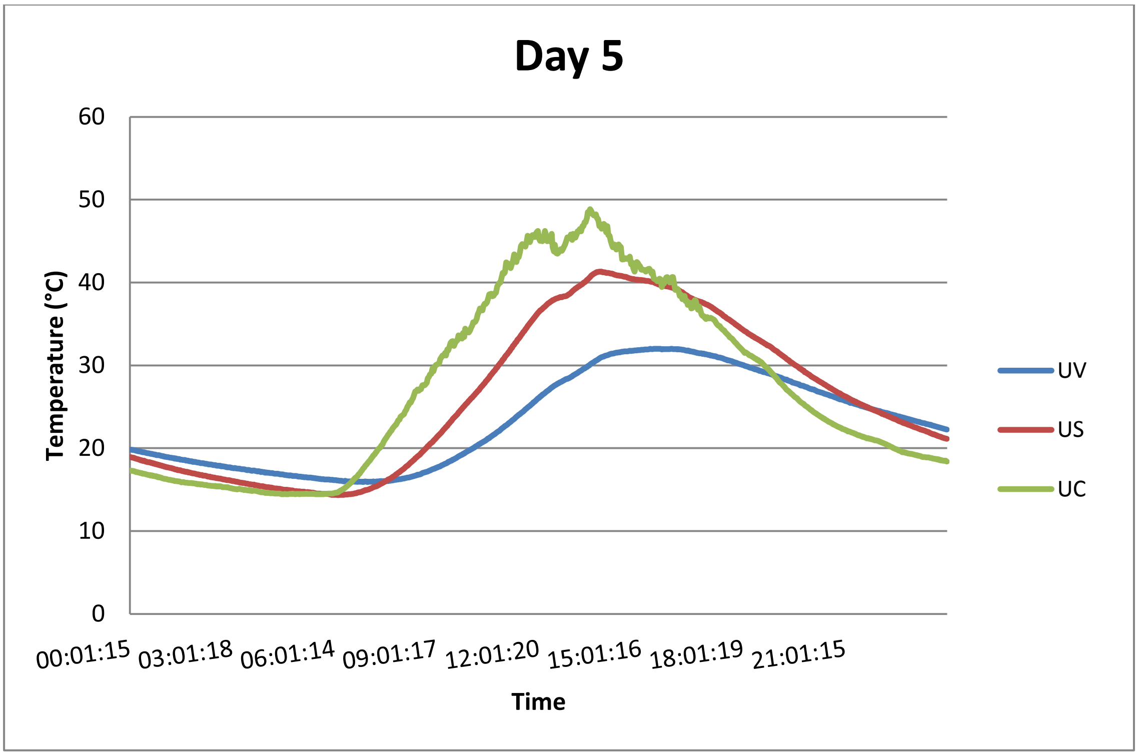

Figure 4-22: Temperature data for Day 5. The abbreviations in the legend are defined in Figure 3-1.

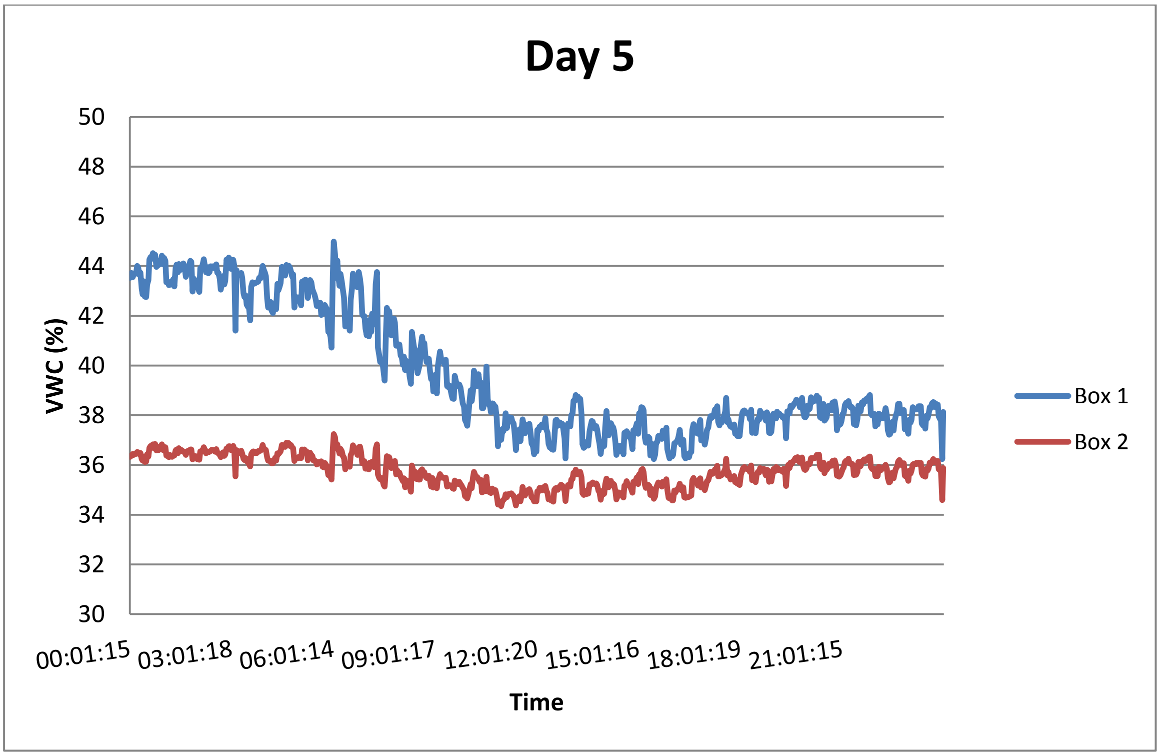

Figure 4-23: VWC for Day 5. Box 1 and Box 2 are defined in Figure 3-1.

4.2.2 Effect of VWC on T_{ave}

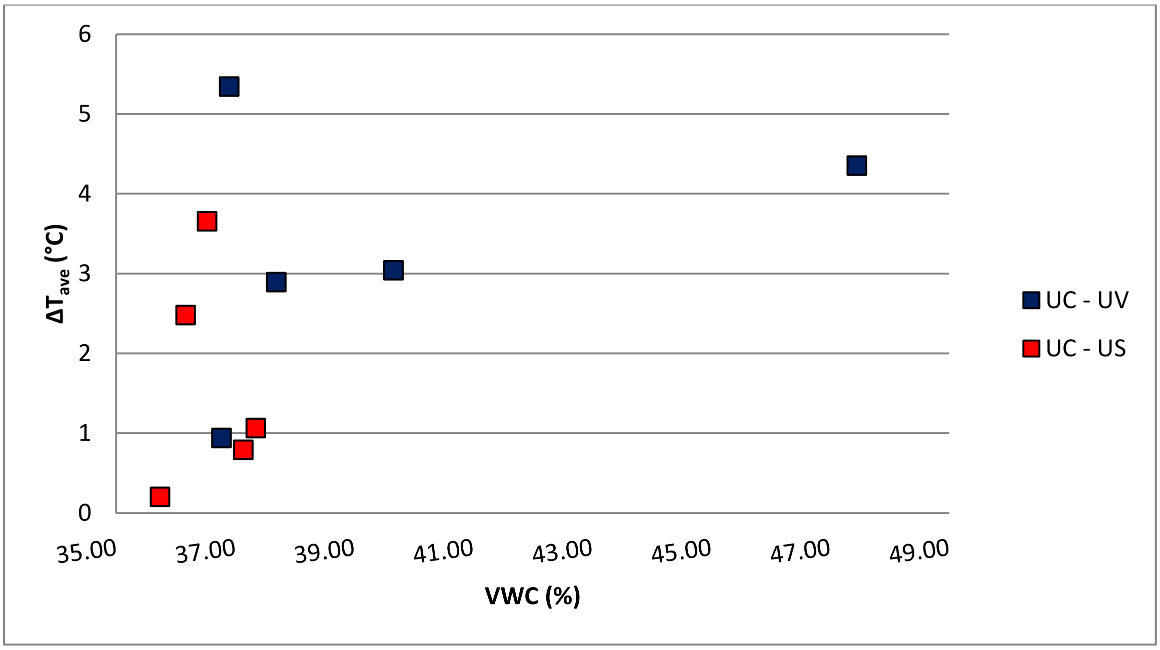

Figure 4-24: Effect of VWC on T_{ave}. The abbreviations in the legend are defined in Figure 3-1.

ΔT_{ave} as a function of VWC for the 5 days is plotted in Figure 4-24. The data shows that ΔT_{ave} remains relatively constant with an increase in VWC; with ΔT_{ave} for the vegetated roof (Box 1) in the region of 3 – 4 °C, and ΔT_{ave} for soil alone (Box 2) in the region of 1 – 2 °C. It is also noted that under the same outdoor weather conditions, the vegetated roof retains a higher level of SWC. It appears that over a wider range of VWC (Box 1), ΔT_{ave} may increase with VWC; but it is not clear from Figure 4-24.

4.2.3 Effect of VWC on A

ΔA as a function of VWC for the 5 days is plotted in Figure 4-25. The data shows that ΔA remains relatively constant with an increase in VWC; with ΔA for the vegetated roof (Box 1) in the region of 20 °C, and ΔA for soil alone (Box 2) in the region of 10 °C. It is again noted that over a wider range of VWC (Box 1), ΔA may increase with VWC; but it is not clear from Figure 4-25.

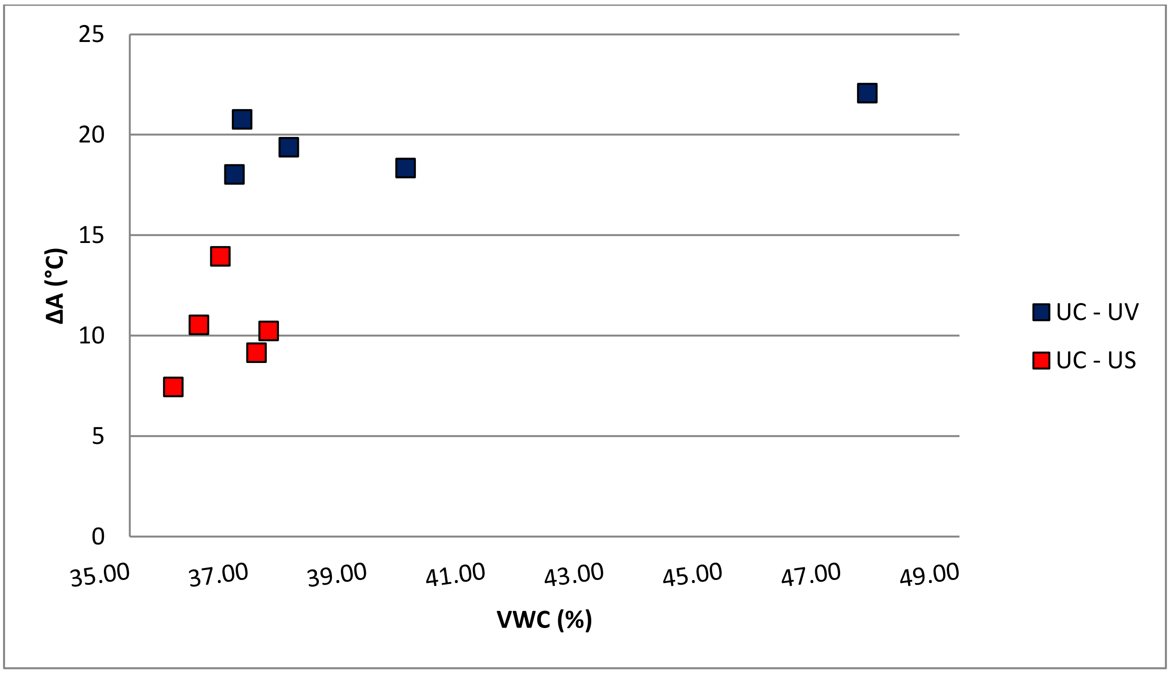

Figure 4-25: Effect of VWC on A. The abbreviations in the legend are defined in Figure 3-1.

4.3 Effect of VWC on the thermal properties of soil

4.3.1 Effect of VWC on C_v

Figure 4-26 shows the relationship between C_v and VWC for the 5 days. As expected, C_v increased with increasing VWC. Higher C_v values mean that more energy is required to raise the temperature of the soil by 1°C. It is therefore expected that T_{ave} and A will decrease with an increase in C_v (and hence VWC). In turn, ΔT_{ave} and ΔA is expected to increase with an increase in VWC. This trend was not strongly observed in Figure 4-24and Figure 4-25.

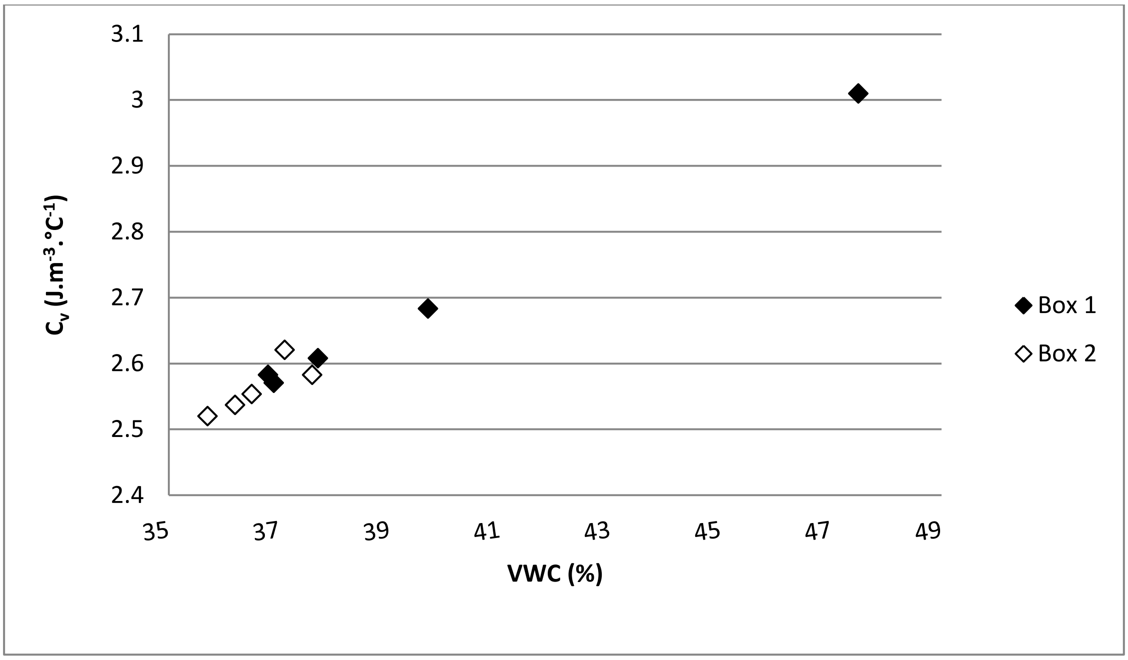

Figure 4-26: Effect of VWC on C_v. Box 1 and Box 2 are defined in Figure 3-1.

4.3.2 Effect of VWC on K_q

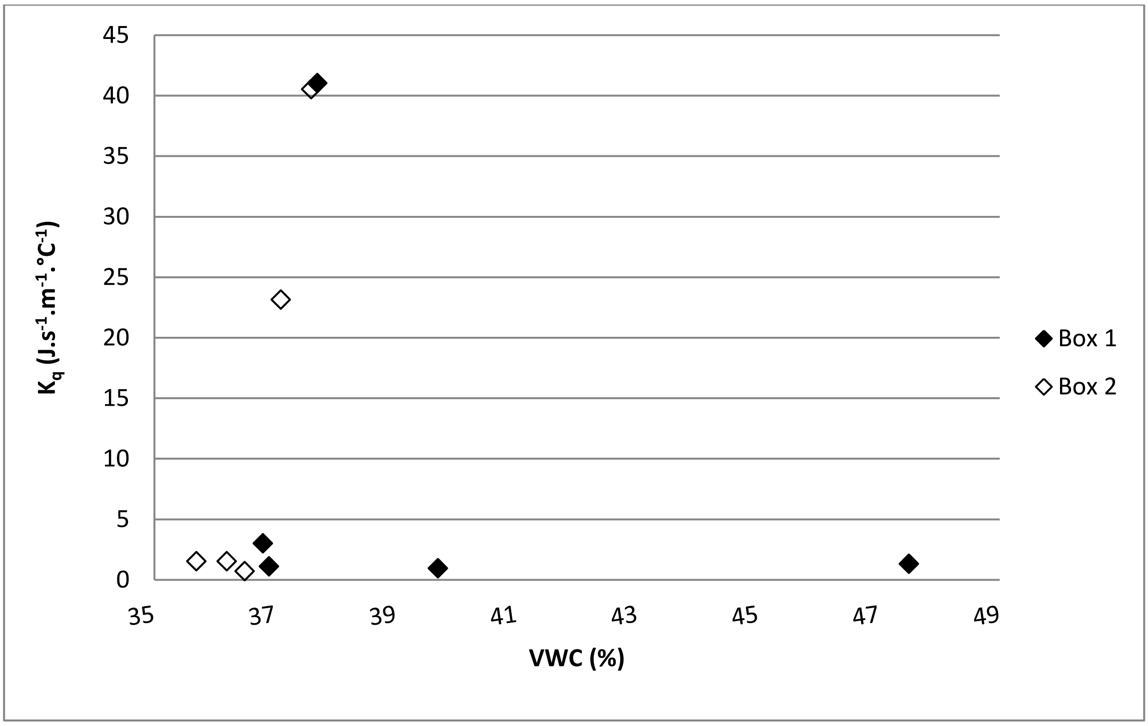

Figure 4-27: K_q as a function of VWC. Box 1 and Box 2 are defined in Figure 3-1.

The effect of VWC on K_q is shown in Figure 4-27. It appears that K_q remains constant with an increase in VWC. K_q was calculated using Equation 2-4. The uncertainty in the exact values of D_q (see section 3.4.2) could contribute to the unexpected trend in Figure 4-27. From literature, K_q estimates of dry to saturated sand range from 0.15-4.0 $J.s^{-1}.m^{-1}.^{o}C^{-1}$ (The Engineering Toolbox, 2011). Some of the results obtained in this study are within this range and some are not. Thermal conductivities recorded in the field can be different from green roof soils because soils used on green roofs have very little organic matter and are generally lightweight.

From previous discussions, it is expected that T_{ave} and A increase with an increase in K_q. This is not observed in Figure 4-24 and Figure 4-25, implying that the effect of K_q on thermal performance indicators is minimal.

4.4 Evapotranspiration effects

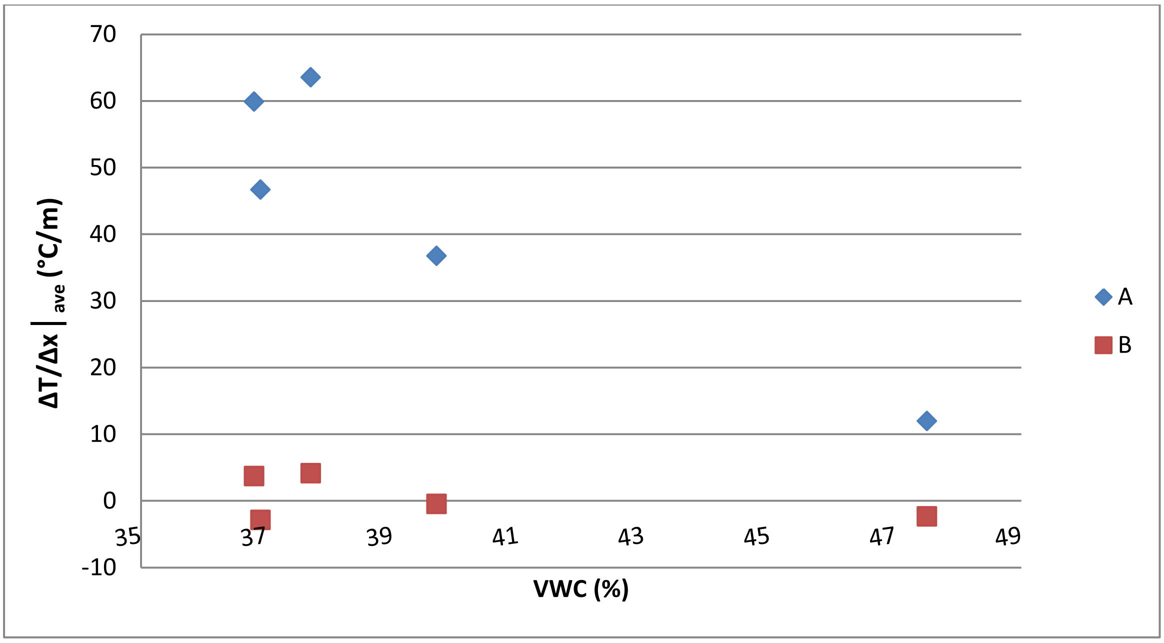

Figure 4-28: Evapotranspiration effects. The abbreviations in the legend are defined in Figure 3-1.

Figure 4-28 shows the vertical temperature gradients [$\Delta T/\Delta x|_{ave}$ (°C/m)] in Box 1 and Box 2 averaged throughout the day and plotted as a function of VWC. Two gradients were plotted: 'A'' between 0.00 m and 0.02 m, and 'B'' between 0.02 m and 0.08 m. Here 'A'' indicates the average flow of energy into the soil body throughout the day, while 'B'' indicates the average temperature gradient within the soil throughout the day. $\Delta T/\Delta x|$ave (°C/m) is the thermal gradient in the direction of the flow

'B'' is constant with VWC, and averages to zero throughout the day. This indicates that net heat inflow is cancelled by net heat outflow. 'A'' tends towards zero with increasing VWC. From the discussion in section 4.1, it is expected that 'A'' should increase with increasing evapotranspiration. Since evapotranspiration increases with VWC, it is expected that 'A'' should increase with VWC. The exact opposite is observed in Fig 4-28. Although contradictory at first glance, this can be explained by observing the VWC of the vegetated versus non-vegetated green roof. There is a tendency for VWC in Box 1 to initially decrease with increasing precipitation probably as a result of evapotranspiration. Therefore the result could very well show an increase in evapotranspiration with VWC.

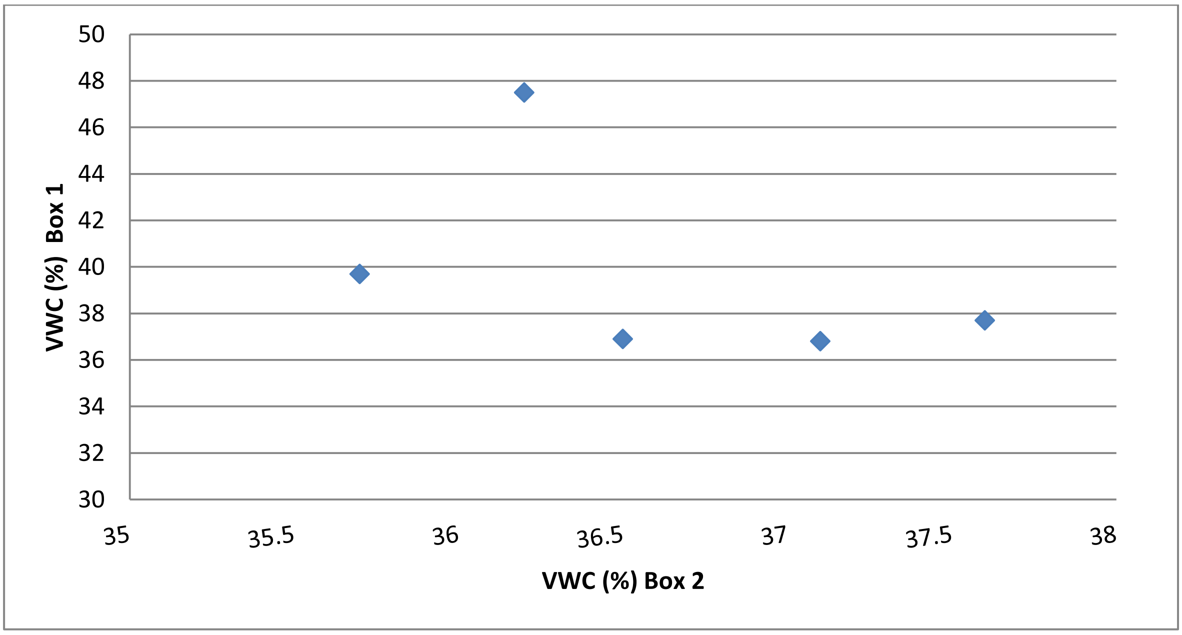

Figure 4-29: VWC of vegetated versus non-vegetated green roof. Box 1 and Box 2 are defined in Figure 3-1.