

GROUND TEMPERATURE AND MOISTURE CONTENT SURROUNDING HORIZONTAL HEAT PUMP COLLECTORS IN A MARITIME CLIMATE REGION

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Abstract: Numerous studies have explored the nature of thermal energy transfer between heat pump collectors and the surrounding ground. These have been mainly conducted in continental climate regions and the findings have recommended that horizontal collectors be submerged at depths of up to 2m to avoid the cooling effects of low temperatures at the ground surface-atmosphere interface. However, shallower arrays are used in maritime climate regions where potential exists for the climate to aid thermal transfer to the collector. This paper reports initial findings of a joint experimental measurement and numerical simulation study undertaken to investigate this potential. The 430m² horizontal collector used was connected to a 15kW heat pump. Presented results show the combined effect of heat pump operation and climate on ground temperature and moisture content about the collector. A simulation model capable of predicting climate induced ground soil temperature and moisture fluctuations to a depth of 2m with a high degree of accuracy is also presented.

Keywords: *heat pumps, ground source, climate, moisture, temperature, gradients*

1 INTRODUCTION

The market for efficient and sustainable technologies has seen steady growth over recent years in Ireland. This was boosted in 2006 when the government introduced grant aid to support the uptake of efficient space and water heating alternatives (Greener Homes Scheme 2006). As of 2007, Irish building regulations require that renewable systems must supply a minimum of 10kWh/m²/annum in space and water heating/cooling and 4kWh/m²/annum in electrical energy to new houses. In the case of heat pumps, the COP must be equal to or exceed 2.5 to satisfy the regulations (Building Regulations 2007). Recognising the dependency of these systems on ground temperature (Burke *et al.* 2008) and good soil heat transfer conditions, it is important to understand the natural energy and mass balance that develops between the climate and the ground (Bose *et al.* 2002). While numerous studies have explored these effects in continental climate regions such as Poland (Popiel *et al.* 2001), and Turkey (Inalli and Essen 2004) and Canada (Hanova and Dowlatabadi 2007), there is a marked absence of similar studies from maritime regions. The later two cited continental studies show the need to bury the collector at depths of between 1 and 2m; to gain protection from low temperatures near the ground surface. However, these guidelines may not be appropriate in maritime climates.

Ireland has a maritime climate, classified as Cfb under the general Koppen-Geiger classification (Peel 2007). Cfb is defined as a temperate oceanic climate with no dry season and an ambient air temperature exceeding +10°C for more than 4 months of the year. Nationally the Irish 30-year-mean average annual air temperature is +9°C, with a maximum of +19°C and a minimum of +2.5°C. On the Irish west coast however the 30-year-mean average annual air temperature is +10.1°C with a maximum of +13.5°C and a minimum of +6.8°C (Met Eireann 2008). This results in a more uniform year round ground temperature,

offering the possibility for higher collector return temperatures about the collector, during the peak heating months, than in continental regions. This offers a natural advantage to increase COP, given that testing of the 15kW_{TH} heat pumps in this study showed a 2.5% increase in COP per degree increase in ground temperature (Burke *et al.* 2008). A similar result was also reported by Wärnelöf and Kronström (2005). Ireland also receives high levels of rainfall all year round, which is another feature of maritime climates. Lohan *et al.* (2006a) highlighted that high soil moisture content is an important factor in maintaining a high thermal diffusivity in the ground above and below the collector. High moisture content aids the transfer of heat from the ground to the collector particularly in the vicinity of the collector as discussed in Redmund *et al.* (1991). This paper builds on previous publications Greene *et al.* (2007), Lohan *et al.* (2006a) and Lohan *et al.* (2006b) by seeking to establish; (i) impact of the climate on the ground temperature and moisture content to a depth of 2m (ii) ability to simulate climate induced fluctuations in ground temperature and moisture content, as a basis for predicting the embodied thermal energy contributed by the climate to the soil surface layer, (iii) the extent and shape of the heat effected zone about the collector, (iv) the rate of ground thermal discharge and recovery generated by heat pump operation.

2 TEST FACILITY

The test facility comprises two identical 15kW_{TH} heat pumps, employing one horizontal collector and one vertical collector heating the Innovation in Business Centre (liBC) building at the Galway-Mayo Institute of Technology, Dublin Road, Galway, latitude $53^{\circ} 16' 39''$ N and longitude $9^{\circ} 00' 43''$ W (Google Earth 2008). The site is 20m above sea level and 1km from Galway bay an inlet of the Atlantic Ocean (Google Earth 2008). This paper's focus is on the horizontal collector and the 860m^3 volume of ground 1m above and 1m below it. The horizontal collector and 15kW_{TH} heat pump are equipped with sensors to monitor thermal output and Coefficient of Performance (COP) as described in Lohan *et al.* (2006b). The collector consists of 25mm outer diameter HDPE piping which is subdivided into ten 130m long circuits, buried at an average depth of 1 meter. Eight of the ten circuits are arranged with in-line formation and two are in SLINKY™ layout. These circuits occupy 430m^2 to the outer most pipes, as shown by the site plan view in Figure 1. The collector has a mean operating flow rate of 69 litres/min, which generates an average temperature rise of 2.65°C across the collector. The heat pump draws approximately 5kW electrical power during standard operating conditions (Burke *et al.* 2008). The region of ground from which the heat pump's collector extracts thermal energy has been instrumented with an array of temperature and moisture sensors arranged in seven vertical ground monitoring profiles about the collector area. The location of these monitoring profiles is shown in Figure 1 as the points identified as P1 through P7. Note that they are positioned at different extremities of the collector region and also under different covers found at the ground-atmosphere interface.

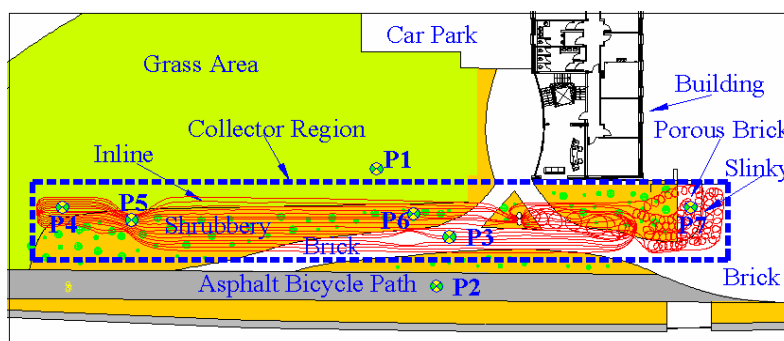


Figure 1: A plan view of the test facility showing liBC building, extent and position of horizontal collector region relative to the liBC, the range of surface covers above the collector and the position of the vertical ground monitoring profiles (P1-P7) (Greene *et al.* 2007)

A detailed vertical elevation through three of these seven profiles, Profile 1 (P1), Profile 6 (P6) and Profile 7 (P7) used in this paper is presented in Figure 2. P1 is positioned outside the collector region and acts as a reference point. P6 and P7 are inside the collector region in areas covered by shrubbery and porous paving respectively. Figure 2, details the number of sensors installed, sensor position and collector depth for P1, P6 and P7.

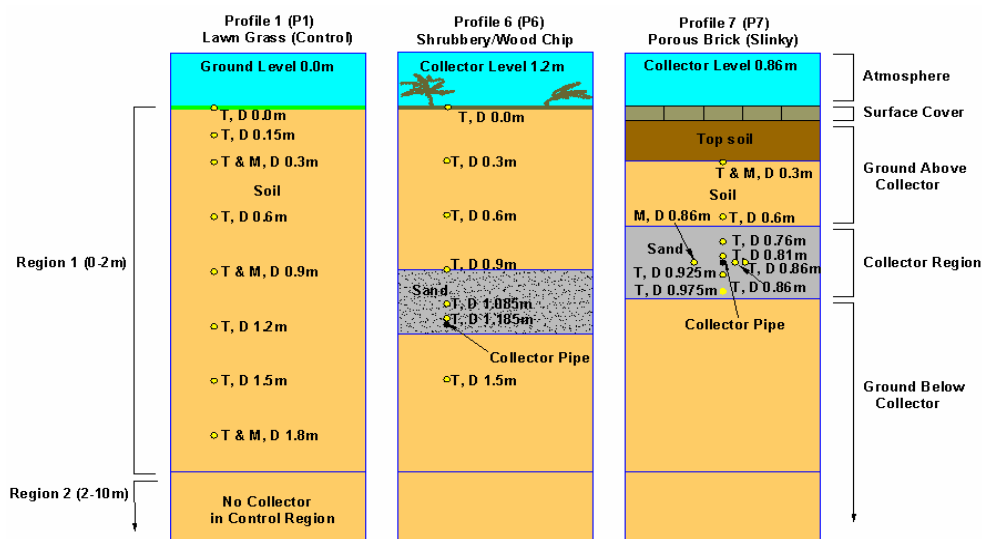


Figure 2: Soil measurement Profiles 1, 6 and 7, showing surface cover, sensor location relative to the surface and collector depth (T=Temperature Sensor, M=Moisture Sensor)

The soil temperature sensors are Class A PT100s with a calibrated accuracy of $\pm 0.35^{\circ}\text{C}$ between 0°C and 100°C . Further on-site calibration in the common Irish soil temperature range of 0°C to 25°C showed that accuracy was within these limits. The moisture content sensors used had a measured accuracy of $\pm 2.5\%$ of volumetric moisture content under laboratory conditions. However calibration is required for the specific soil type that the sensors will operate in. For this reason only moisture data from P1 is presented, as P1 is the most homogenous profile with a reasonably consistent Particle Size Density (PSD) being measured to a depth of 0.6m. An extensive weather station has also been established at the test site and a list of climate sensors used and calibrated accuracy is presented in Table 1.

Table 1: Climate variables measured and sensor accuracy

No.	Climate Variable	Accuracy
1	Rainfall Levels	$\pm 2\%$ up to 25mm/hr
2	Rainfall Temperature	$\pm 0.35^{\circ}\text{C}$ @ 0°C
3	Wind Speed	± 0.3 m/s
4	Wind Direction	$\pm 3^{\circ}$
5	Air Temperature	$\pm 0.35^{\circ}\text{C}$ @ 0°C
6	Air Pressure	$\pm 0.5\text{mbar}$ (50pa) @ 20°C
7	Relative Humidity	$\pm 2.5\%$ @ (10-100% RH)
8	Net Solar Radiation	$\pm 10\%$ of daily totals
9	Net Infrared Radiation	$\pm 10\%$ of daily totals

Weather conditions are monitored at 5 minute intervals year round for the to (i) help explain fluctuations in both soil temperature and moisture content; (ii) build an accurate database of the dominant local climate and compare it with other regions within Ireland's climate classification; (iii) use the database of climate data to compare local conditions with those of other regions where similar heat pump systems are being researched and (iv) monitoring

climate data to assess the collector areas thermal energy balance over long time periods at deep levels and short time steps near the surface.

3 CLIMATE AND THE THERMAL-ENERGY BALANCE ABOUT THE COLLECTOR

It is important to recognise that horizontal collectors not only extract heat from the ground layer above it, which is most sensitive to the climate, but also from the ground below it which is more stable and reflects ground conditions at greater depths. Since the ratio of these two sources has not been definitively quantified in the literature, the following energy-balance analysis considers both climate effects on the ground above the collector and on the deep layer below it. Like most of Northern Europe with the exception of Iceland, Ireland is "impoverished in geothermal resources, mainly because it lies outside the sphere of recent Alpine tectonic activity and is distant from plate boundaries" (Allen *et al.* 2003). The average ground temperature gradient in Ireland varies from 10-15°C/km in the south to 25-30°C/km in the north of the Island (CSA Group 2004). This is equivalent to a 0.01°C/m gradient in Galway. Data returned by temperature sensors installed in the 100m deep vertical boreholes at GMIT are in agreement as they show a 0.5°C increase in ground temperature between 50 and 100m depths during a 6 month period before the heat pump was first turned on. For this reason, the main driver in Ireland's soil thermal-energy balance is climate. The soil energy balance in Ireland is influenced predominantly by air temperature and solar exposure. In many regions around the world air temperature and solar exposure are closely related, however Ireland's situation is complicated by its proximity to the Atlantic Ocean in two ways. Firstly, Ireland's oceanic climate leads to temperate conditions like all maritime regions and secondly, the Gulf Stream, a flow of warm air from the Gulf of Mexico driven by thermohaline circulation in the Atlantic, produces mild winter air temperatures (Bryden and Imaewaki 2001).

For the purposes of this paper and in order to discuss the influence of climate on the soil energy balance in Galway, three regions that display differing degrees of climate sensitivity are defined. As indicated in Figure 1, Region 1 is the shallow layer from 0-2m, which is naturally subject to year-on-year changes but is also affected by seasonal fluxes and weather changes within seasons as seen in Figure 3(a). Region 1 is also subject to diurnal patterns along with short-term effects of recent weather as can be seen in Figures 4 and 5. Region 2 is defined to occupy intermediate depths of 2-10m. Ground temperatures within Region 2 exhibit fluctuations associated with yearly shifts, seasonal patterns and also changes within seasons but to a lesser extent than Region 1. Seasonal shifts are often dampened by 5 to 6m depths as demonstrated by the data emanating from Poznan, Poland, Figure 3(b). Finally, Region 3 is the deep soil layer at depths greater than 10m, well below the point of convergence of the annual maximum and minimum lines from Poland in Figure 3(b). Region 3 is subject only to the effects of large year-on-year changes in climate history. Researchers such as Halozan and Rieberer (2005) have identified the 10-15m depth as the point where relatively constant temperature can be expected over a year. Given reasonably steady year-on-year conditions, this would apply over a number of years while only large-scale climate shifts would effect the energy balance down below 10-15m. Given that this work is concerned primarily with horizontal collectors that are typically buried at a depths of 1m in Ireland, Region 3 has been omitted from the following analysis.

Figure 4 overlays extracts from climate data on soil temperature measurements from Profile 1, recorded over the 12-month period between February 2007 and January 2008. During this period the average mean daily air temperature was +11.04°C with a maximum of +20.52°C and a minimum of +0.19°C. The data presented represents daily averages of incoming solar radiation, air temperature and soil temperature at seven different depths to 1.8m. Figure 4 (a) and (b) give a good indication of the influential effect of Ireland's maritime location and the Gulf Stream in particular on Ireland's air temperatures. It can be seen from the mean seasonal (Irish spring begins on 1st February) solar radiation and air temperature values in Figure 4 (a) and (b) that, while sunshine was approximately half of summer levels in the

autumn season, the average temperature is only 0.2°C lower. Similarly, average winter radiation is only one fifth of spring radiation, however there is only a 0.14°C difference in the mean seasonal air temperature. A combination of the test sites proximity to the Atlantic Ocean and the effect of the Gulf Stream reduces air temperature fluctuations over the year.

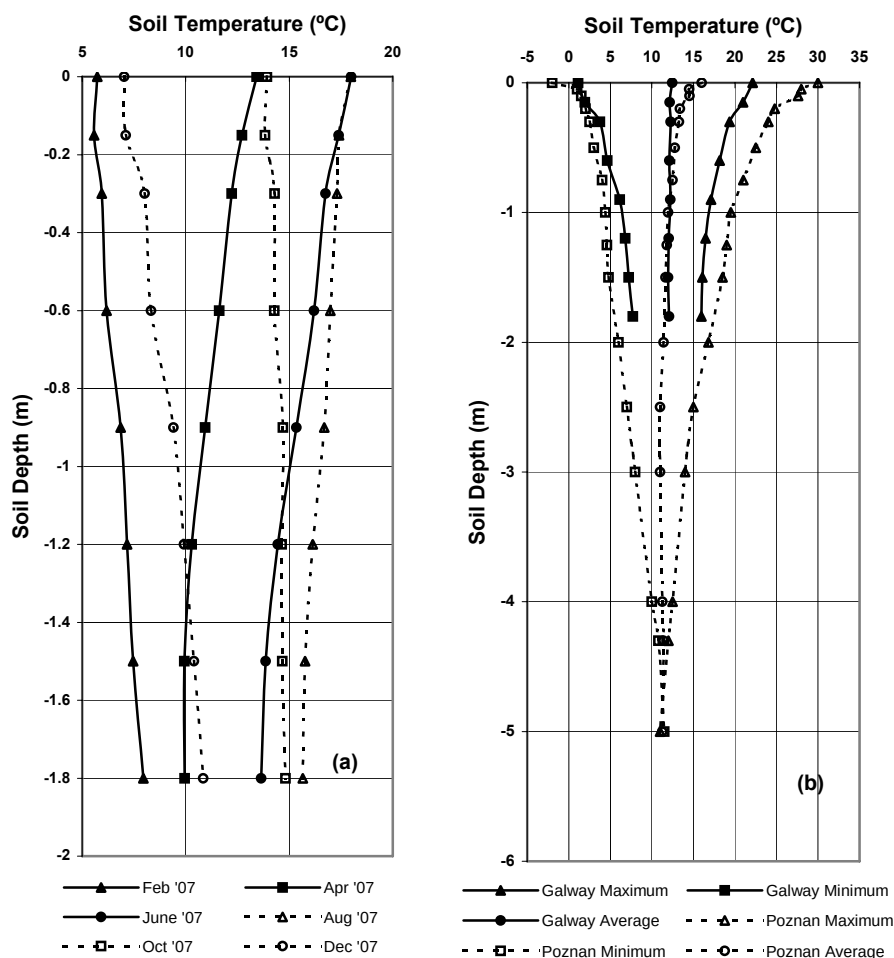


Figure 3: (a) Bi-monthly average temperature gradients in P1 from Feb 2007 to Dec 2007, (b) annual maximum, minimum and average temperature gradients from P1, Galway (Feb 2007 - Jan 2008) and Poznan test site, Poland (2000) (Popiel et al. 2001)

Figure 4 (c) and (d) demonstrate the interaction between the climate parameters in 4(a) and 4(b) and soil temperatures at depths of up to 1.8m (Region 1) in P1. In Figure 4(c) and 4(d) radiation and air temperature have clear effects on the surface temperatures and this effect propagates downward. In summer, solar radiation dominates both soil and air temperature by heating the surface first and then the air. The absence of radiation during winter diminishes the potential of the ground surface to heat the air. While this would lead to a drop in both soil and air temperatures in many regions, winter air temperatures in this site remain stable and relatively high due to proximity of the 'warm' ocean. Air temperature becomes the dominant factor in driving the soil surface energy balance. As in summer the soil surface continues to loose thermal energy via radiation during winter nights but fails to receive as much incoming solar radiation during the winter days. However, the air heats the soil sensibly during the day and for this reason the soil temperature assumes the air temperature signal. Seasonal effects and effects within seasons are clear to a depth of 1.8m (Figure 4(c)). There are two transition points at mid-autumn and mid-spring because the near surface temperatures are higher in summer and early autumn while the deeper layers retain higher temperatures in winter and early spring. There is clear attenuation of the wave amplitude of surface effects and phase shift of each wave with increasing depth as described by the standard diffusivity dependant model presented in Campbell and Norman (1998).

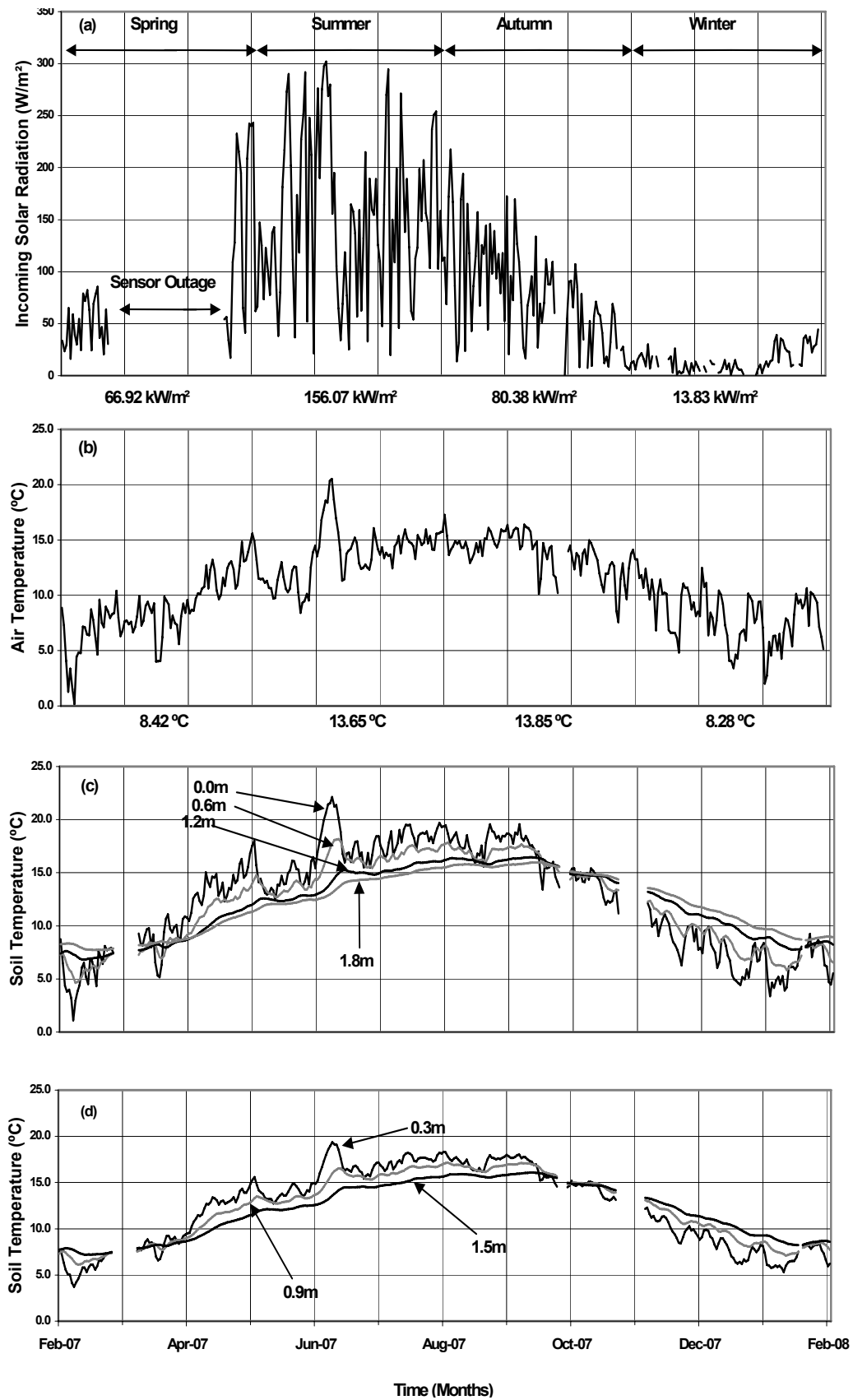


Figure 4: (a) Average daily incoming solar radiation (b) average daily air temperature (c) average daily soil temperature at 4 depths in P1 the control location (d) average daily soil temperature at 3 additional depths also in P1.

While solar radiation and air temperature dominate the soil energy balance in the long-term (3 months to 1 year), particularly in Region 2 and at the greater depths of Region 1, the short term balance at the soil surface and the short term propagation of surface energy fluxes to shallower depths of Region 1 is more complicated. This can be more accurately described as an energy and mass balance, primarily because of the degree to which evaporation from the soil surface effects surface temperature and given that energy movement in the porous, unsaturated medium below the surface is a process of combined heat and mass transfer.

Over short time periods (1 day to 1 month) the solar radiation, air temperature, relative humidity, rainfall levels and the wind speed affect the surface energy and mass balance. In the past the majority of work in this field was concentrated to the agricultural-meteorology sector, where Soil Vegetation Atmosphere Transfer (SVAT) models were developed. Typical SVAT models in existence include the JULES model developed by the United Kingdom's Met Service and the COMPASS model from Cardiff University, the later of which includes the combined heat and mass transfer model of Thomas (1985). However, the Simultaneous Heat And Water (SHAW23) model from the US Department of Agriculture is one of the most commonly used SVAT models and is used in this study. Technical details of SHAW23 can be found in Flerchinger (2000), samples of calibration are presented in Flerchinger *et al.* (1997; 1998). Finally, Hymer *et al.* (2000) presented testing and review of the SHAW23 model. The SHAW23 model was applied in this study to simulate temperature and moisture fluctuations in P1 for the month of December 2007. Results of this simulation are displayed in Figures 5 and 6 including the weather inputs over the simulation period. For clarity, wind speeds, which averaged 15.42 m/s (34.7 mph) over the simulation period, have been omitted from Figures 5 and 6. The relevant properties of the soil at the test site are presented in Table 2.

Table 2: Soil properties from Profile 1 (P1 in Fig. 1) used as inputs for SHAW 23 model, PSD based on USDA guidelines (Marshall *et al.* 1979) (θ_v = Volumetric Moisture Content)

Soil Sample	Bulk Density	PSD			Saturated θ_v
Profile 1	kg m ⁻³	% Sand	% Silt	% Clay	m ³ m ⁻³
0.3 & 0.6m Depth	1650	60	30	10	0.38

The model consists of a one-dimensional nodal system, where nodes represent the boundary between soil type layers. The PSD and bulk density presented in Table 2 are required for each layer along with surface properties, such as albedo. In the case of P1 the surface cover is grass and the surface properties are available from the software library. Other input data required includes the upper boundary conditions such as the hourly weather fluctuations of incoming solar radiation, air temperature, wind speed, precipitation and humidity over the simulation period. There are two options for the lower boundary condition in the software. Measured temperature and moisture data at the lower boundary can be used or the lower boundary is set to a sufficient depth where it is possible to estimate constant levels of temperature and moisture content over the simulation period. In this simulation, data readings from 1.8 meters were input for both temperature and moisture content. Figure 5 shows that temperature predictions were accurate to within a maximum error of $\pm 0.8^\circ\text{C}$ and $\pm 0.4^\circ\text{C}$ at 0.15m and 0.9m respectively. While predicted and measured moisture data showed good correspondence (maximum error $\pm 0.05\text{m}^3/\text{m}^3$) at the 0.3m depth as shown in Figure 6, such predictive accuracy might be explained by the close proximity of this location to the upper boundary condition. The same high level of predictive accuracy achieved for ground temperature at intermediate depths was not achieved for moisture content. This corresponds with similar trends reported by Hymer *et al.* (2000). Better accuracy was also found near the lower boundary condition, to be expected, given that this boundary is controlled by actual measured data. However at intermediate levels such as 0.9m, predictive accuracy diminished considerably.

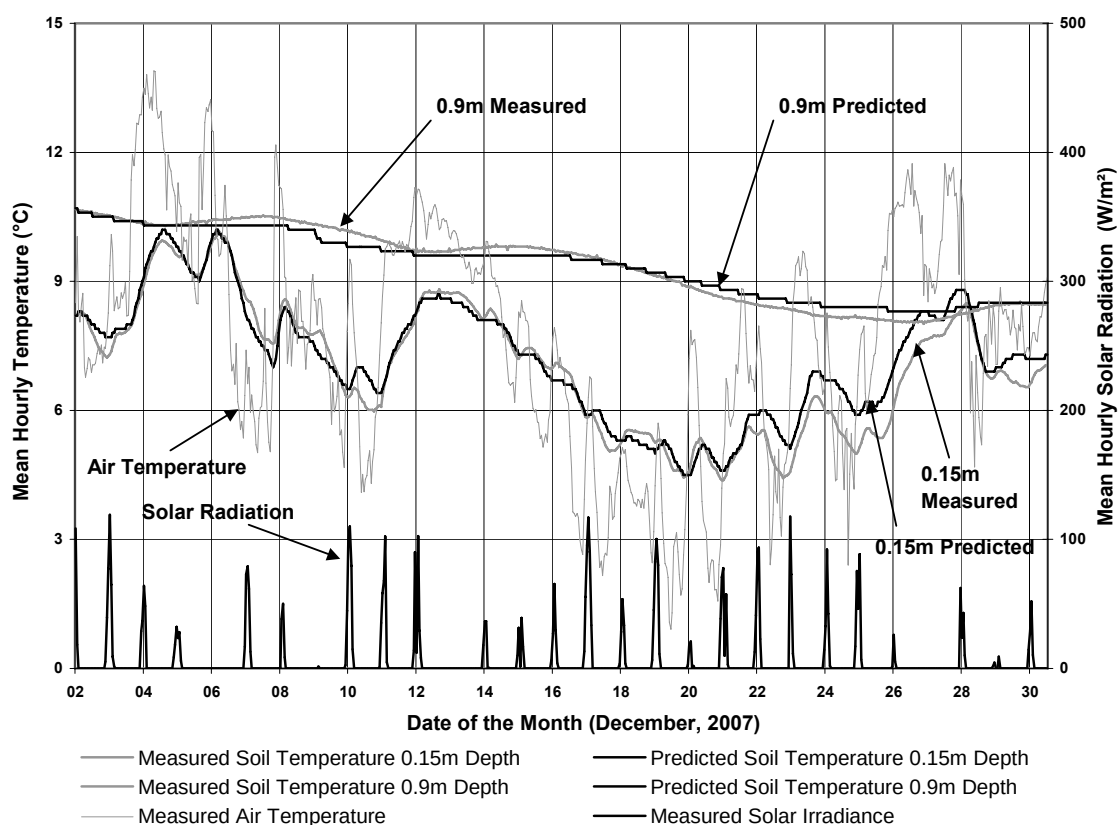


Figure 5: Measured and predicted soil temperatures at 0.15m and 0.9m depths in P1 during December 2007 with air temperature and incoming solar radiation variations over the same time period

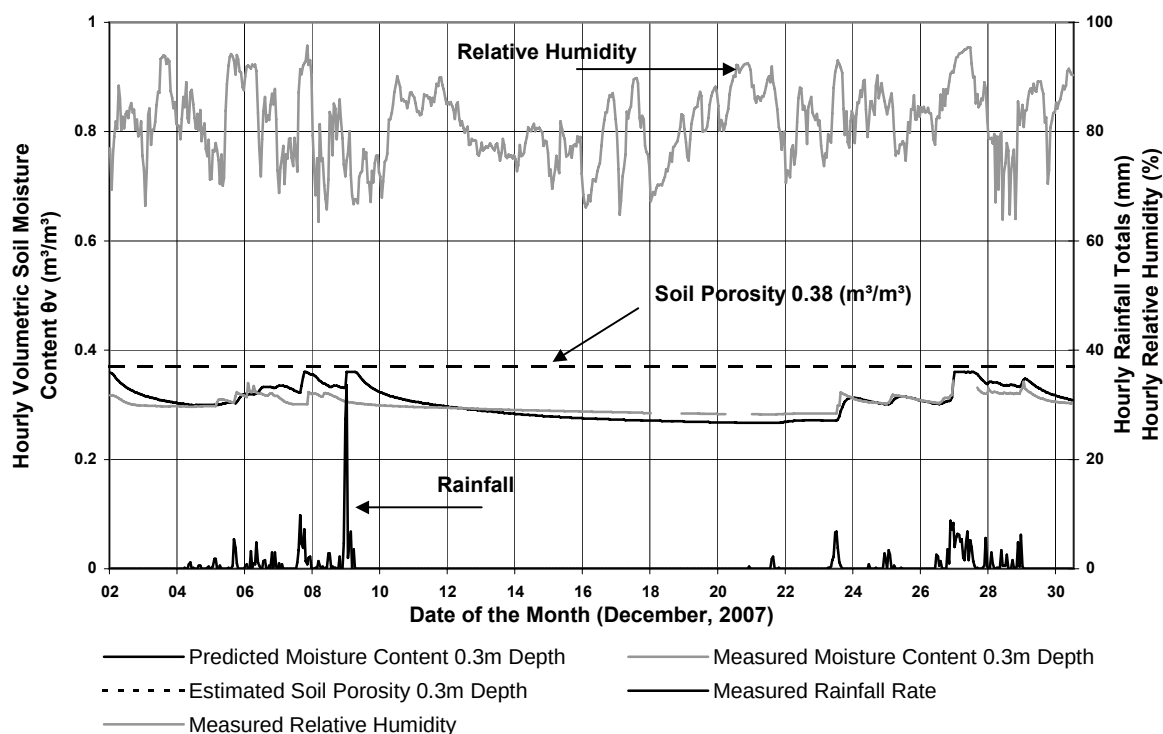


Figure 6: Measured and predicted volumetric soil moisture content at 0.3m depth in P1 during December 2007 with rainfall levels and relative humidity variations over the same time period

This may be attributed to the migration of finer clay particles to depths of approximately 1m after the sensors were installed. Finer particles often create impermeable layers, which hold large amounts of water but do not allow water to move easily upwards or downwards. The model does not account for this and further research is required.

4 HEAT PUMP OPERATION AND GROUND TEMPERATURE GRADIENTS

While it has been established that the ground energy balance is driven by the climate in Ireland with the amplitude and extent of temperature fluctuations in Regions 1 and 2 being quantified and discussed in section 3, this balance is disturbed by the operation of the heat pump's horizontal collector. However, during the late spring, summer and early autumn the heat pump is turned off, thereby allowing the ground conditions return to the natural energy balance equivalent of a region without a heat collector or indeed a region outside the influence of the collector as discussed in Section 3. Figure 7 demonstrates the impact of heat pump operation for the first operating sequence in a new heating season, during October 2007. Since the heat pump had been turned off since May 2007 the soil temperatures inside and outside the collector region had achieved a uniform temperature of approximately 14.75°C as shown in Figure 7 between October 12th to 6 am on October 15th. However, once the heat pump is activated on the 15th thermal draw down of the collector region is displayed.

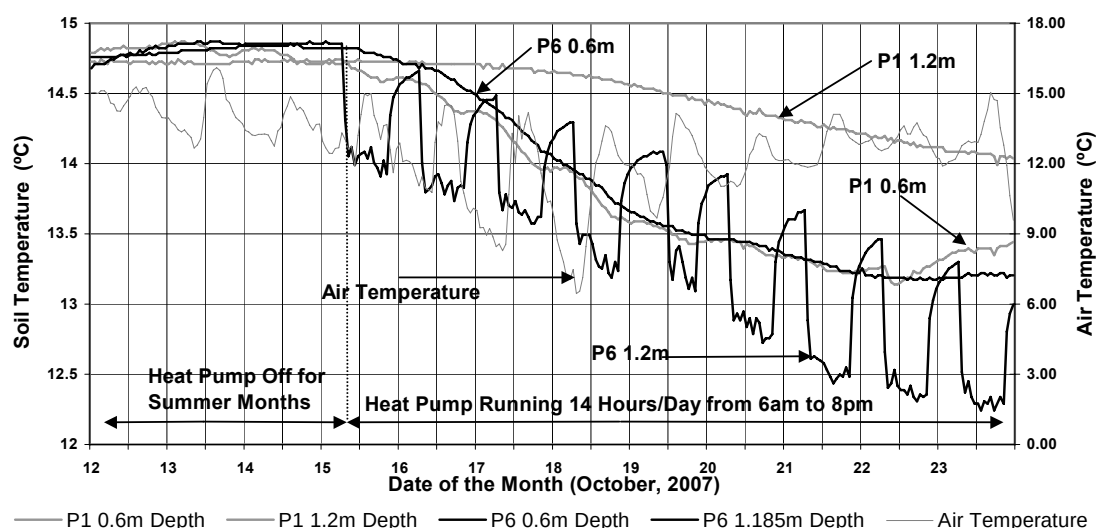


Figure 7: Ground temperature measurements from P1 and P6 between October 12th and 23rd 2007 along with air temperature measurements for the same time period.

During the 14-hour daily operating cycle, with an hourly-averaged extract rate of 6.5kW, the maximum temperature difference between P1 and P6 at the 1.2m collector depth, increases from 0.85°C to 1.85°C over the 8-day operation period between the 15th and 23rd of October. While the heat pump is off for 10 hours a day the ground recovers but the minimum temperature difference between P1 and P6 at collector depth increases from 0.1°C to 0.8°C over this period. However this increase does not continue indefinitely, given a period of 7-10 days collector depth temperatures reach quasi-steady-state with the collector region ground temperature remaining approximately 1.85-2°C below the equivalent temperature at that depth, outside the collector region during continuous steady operation.

In an effort to show the transient and accumulating impact of heat pump operation on soil temperatures in the surface layer, Figures 8 (a) and (b) present a series of vertical soil temperature gradients recorded at equally spaced time intervals of 24 and 48 hours respectively during the period October 14th to 23rd presented in Figure 7. These graphs show the extent of ground temperature change in the soil layer adjacent to the collector pipe as well as in the surrounding soil layers above and below the collector.

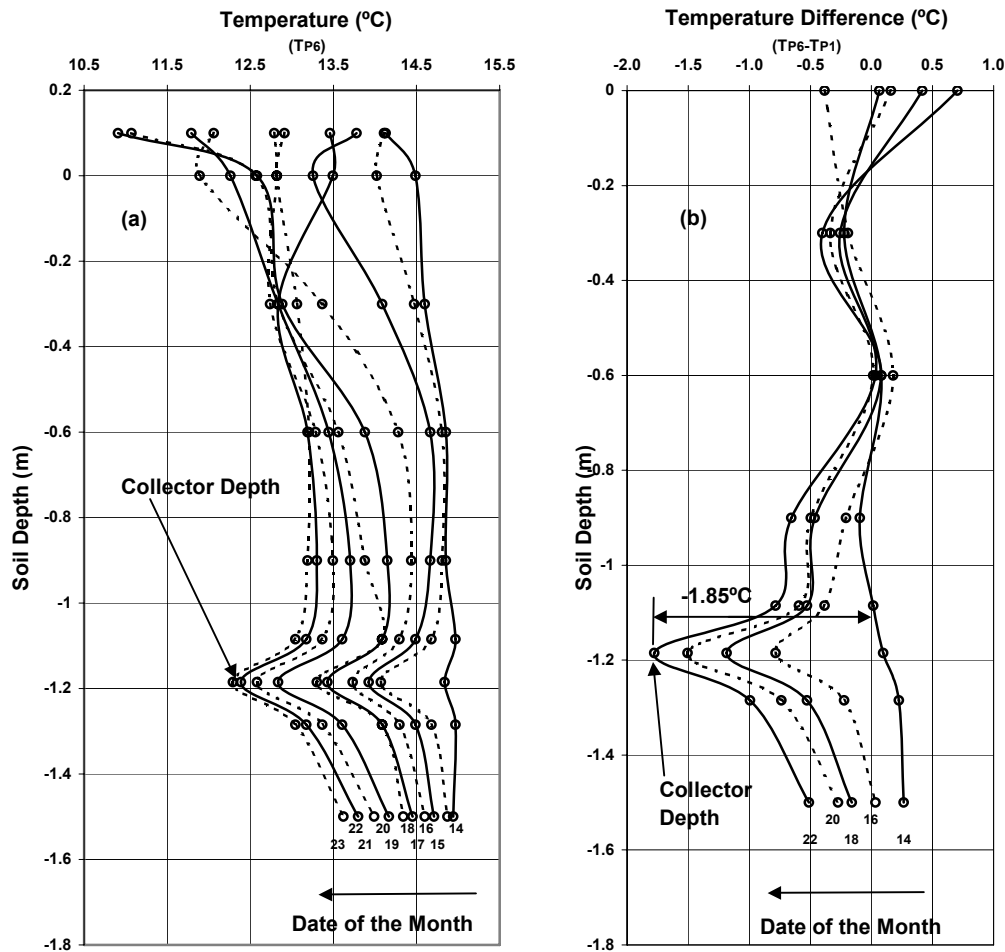


Figure 8: (a) Series of soil temperature measurements taken at 24-hr intervals at midday each day in P6 (T_{P6}) over the period October 14th to 23rd, 2007 including air temperature above the surface, (b) series of soil temperature differences between inside and outside the collector region ($T_{P6} - T_{P1}$) taken at 48-hr intervals at midday, every second day over the period October 14th to 23rd 2007

Figure 8(a) represents the combined effects of air/surface temperature changes and heat pump operation over the period on the shallower depths of P6, while Figure 8(b) seeks to remove the effect of climate and displays the effect of just heat pump operation by presenting the temperature difference between P1 and P6 ($T_{P6} - T_{P1}$) at 48-hour time intervals. It can be seen in Figure 8(b) that on the 22nd after 8 days of operation at an hourly average extract rate of 6.5kW (accounting for on/off cycling) over 14 hours that the temperature difference ($T_{P6} - T_{P1}$) at collector depth is 1.85°C. In Figure 8(a) there is less than 0.1°C temperature change at collector depth between the 22nd and the 23rd, this is the 1.85-2°C control-collector temperature difference of the steady state condition proposed earlier. Most of the energy comes from the region 0.4m above and below the collector and the data indicates that more energy is supplied from below the collector. However, this requires further study with sensors placed deeper beneath the collector.

5 CONCLUSIONS

A thorough experimental facility has been established to investigate the impact of climate and heat pump operation on soil temperatures to depths of 2m. It has been shown that geothermal gradients are very small in Ireland, with climate being the major driver in the Irish ground energy balance. The time period and depth penetration of different climate fluctuations are discussed in relation to the buried depth of horizontal heat pump collectors in

Ireland. It is shown that the effect of hourly weather fluctuations on the surface energy and mass balance and the propagation downward to 2m can be modelled accurately. Further work is required to explore the thermal energy balance above and below the collector and the moisture gradients in the collector region. The effect of thermal depletion of the ground source as well as long-term (summer), and short-term (10 hours) recharge has been displayed. The importance of proper collector sizing and the use of rest periods for the ground source merits further research and work is underway to produce operating guidelines.

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